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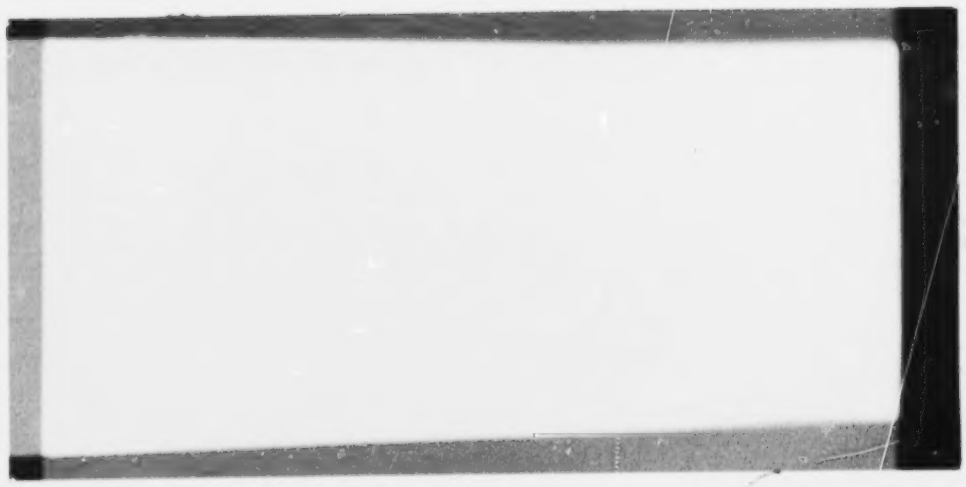

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16. Abstracts
An assessment was made of the economic impact of air pollution on electronic components. To begin the study, electronic components were divided into eleven different categories as defined by the Department of Commerce. The manner and amount of damage from air pollutants that might have been expected in each of these component categories was assessed by surveying the literature describing pollutant material damage mechanisms. The expected effects were compared with the actual experience of major manufacturing companies which appeared to account for most of the sales in each category. Where the literature survey indicated that gaseous sulfur compounds, notably sulfur dioxide, should be expected to account for most of the damage to electronic components, interviews with manufacturers revealed that particulate matter, actually was responsible for most of the electronic component and equipment malfunctions currently being experienced. The economic effects, which were represented by three cost categories, were applied to each component category and then summed to arrive at a total cost of about 15.5 million.

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A SURVEY AND ECONOMIC ASSESSMENT OF THE EFFECTS OF AIR POLLUTANTS ON ELECTRICAL COMPONENTS

Volume I
Sections 1 through 9

PREPARED FOR
DIVISION OF ECONOMIC EFFECTS RESEARCH
AIR POLLUTION CONTROL OFFICE
ENVIRONMENTAL PROTECTION AGENCY
ATTENTION: MR. JAMES B. UPHAM

FINAL REPORT ON
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August 1971

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SUMMARY

An assessment was made of the economic impact of air pollution on electronic components. The study was performed for the National Air Pollution Control Administration, now the Air Pollution Control Office of the Environmental Protection Agency, during the latter part of 1970 and extending into the spring of 1971.

Electronic components were divided into eleven different categories as defined by the Department of Commerce. The manner and amount of damage from air pollutants that might have been expected in each of these component categories was assessed by surveying the literature describing pollutant material damage mechanisms. The expected effects were compared with the actual experience of major manufacturing companies that in total probably accounted for most of the sales in each category. Where the literature survey indicated that gaseous sulfur compounds, notably sulfur dioxide, should be expected to account for most of the damage to electronic components, interviews with manufacturers revealed that particulate matter, acting in at least five different ways, actually was responsible for most of the electronic component and equipment malfunctions currently being experienced.

An attempt to relate levels of particulate concentration with equipment failure rates by means of a statistical analysis was not conclusive.

The economic effects of air pollution were represented by three cost categories. These were applied to each component category and then summed to arrive at a total annual cost of about $15.5 million.

1. INTRODUCTION

Air pollution is costly in its effects, its control, and its abatement. It damages materials, degrades performance or, in extreme cases, leads to catastrophic failure; and these are only the physical effects. Biological effects, especially those perceptible to humans, can be equally devastating. Materials and components are costly to replace, repair or clean; protecting these things from damaging pollutants or abating the source of pollutants, if this is even possible, may be more costly.

This aspect of air pollution has been surmised for as long as air pollution has been a disturbing factor in our economy, but only recently have studies been undertaken to make quantitative assessments of the magnitude of its economic impact. These studies have been conducted by the Materials Branch of the Economic Effects Research Division, Air Pollution Control Office, a major component of the Environmental Protection Agency, and are designed to answer the question, "How much does air pollution cost?" The data from this study, "An Assessment of the Economic Impact of Air Pollution on Electrical and Electronic Components," will add to that already accumulated in several other studies.

The primary objective of the study was to answer the question, "How much does air pollution cost the electrical and electronic industry?" The electrical and electronic industry is, of course, much too large to be encompassed by a single study such as this, but, fortunately, the field can be delineated rather easily. The method for doing so, described more fully in Section 2, consisted essentially of obtaining an inclusive categorization of electronic components from a U. S. Department of Commerce publication, and then referring to several other publications to select a list of representative companies in each category.

Thus, when "electrical and electronic industries" are referred to in the report, the reader will recognize that the term is meant to be all-inclusive, but that specific data usually will be an extrapolation of results obtained from a sampling procedure.

The current state of knowledge of the mechanisms by which air pollution damages materials and components was assessed by surveying all available literature on the subject. The primary purpose of the survey was to provide a basis for meaningful discussions with electrical manufacturers at a later date, and these in turn led to the perception of damage mechanisms not discovered in the literature.

This is the framework within which the survey of electrical and electronic manufacturers is presented. Initially, it was believed that between 50 and 60 contacts would yield a statistically significant sample. When early results revealed a disappointing paucity of data, the sample was expanded to over 100. In contacting manufacturers, an effort was made to interview the Manager of Manufacturing, the Manager of Engineering, the Manager of Quality Assurance, or some other highly placed individual who was fully cognizant of the company's manufacturing methods and of the steps necessary to assure a high-quality product. Further discussion would elicit information necessary to determine which of these steps were necessary to reduce the effects of air pollution. Except in a few isolated cases, however, it proved to be difficult to assign an unambiguous cost to these measures, and in no case was it possible to determine from interviews with manufacturers a quantitative relation between rejection rates and air pollution.

Several users of electronic equipment, on the other hand, maintained carefully detailed records of failure rates, and by comparing these data with air quality data obtained in the immediate locale, statistical relationships were calculated.

It is gratifying to note here the cooperative responses obtained from almost all of the persons interviewed. Almost without exception, each individual became interested in the project when its purpose was explained to him, and supplied the requested information without reservation.

As was to be expected, however, the amount of information varied widely from one manufacturer to another. In by far the majority of cases, no added manufacturing costs were uncovered which could be related

solely to air pollution. In many cases, preventive measures such as clean rooms, filters and the like would have been installed even if the plant had been located in the cleanest spot on earth. In some cases, the manufacturer first became aware, as a result of our interview with him, that air pollution might be a problem. In a few cases, we encountered companies which had had unusual experiences or had maintained comprehensive records or were taking unusual control or abatement measures. These companies were visited and, when possible, case histories were prepared describing the situation.

An additional major objective of the survey was to obtain data needed to determine total annual cost. This was done by extrapolating preventive costs, maintenance costs, and residual costs, all estimated from interview data, to annual nationwide or industry-wide costs on a case-by-case basis and then combining them into a total.

The number obtained in this way is subject to two uncertainties. First, gaps in the data were identified during the study. Second, the need to contain the study within prescribed time and cost limitations means that some areas of possible significance have been omitted. On this basis, we estimate that the total annual cost of air pollution to electronic components is $15.5 million and that the figure may be uncertain by $\pm$ 30%.

2. THE ELECTRONIC COMPONENTS INDUSTRY

There are almost 150 recognizable products distinguishable as electronic components [1] and approximately 1450 companies in the United States that manufacture them. [2] To assess the economic impact of air pollution on these manufacturers, it is necessary to classify all of the components into manageable categories and then to select groups of manufacturers who will represent each category. The object, of course, is to select the classification system so that the conclusions resulting from this study will be statistically valid representations of the entire industry.

2.1 CHARACTERIZATION OF THE INDUSTRY

In a broad sense, the electronic industry is engaged in applications of that branch of science and technology which deals with techniques and devices to direct and control the conduction of electricity through a gas, vacuum, liquid or solid state material.

More specifically, for purposes of this report, we shall define the Components part of the Electronic industry to include companies engaged in the manufacture of the types of devices listed in Table 2-1. This is the categorization developed and utilized by the Business and Defense Services Administration (BDSA) of the United States Department of Commerce, [1] and was selected because (a) the number of categories is easily manageable; (b) each category is relatively homogeneous, that is, the components contained in each category are sufficiently similar to permit straightforward economic analysis; and (c) because statistical and economic data were available in these categories.

The magnitude of each component category is also shown in Table 2-1. Semiconductor devices and integrated circuits represent over one quarter of the total electronic components industry and, as will be seen, they are also among the components most susceptible to the effects of air pollution.

An alternate classification scheme would have been the Standard Industrial Classification (SIC) established by the Bureau of the Budget in 1967. This

Table 2-1. Electronic Component Categories

Component Category	1969 ($ Million)*	Percentage of Market
Semiconductor devices	936	19.2
Integrated circuits	751	15.4
Television picture tubes	613	12.6
Capacitors	472	9.7
Resistors	434	8.9
Power and special purpose tubes	380	7.8
Connectors	372	7.7
Transformers	315	6.5
Relays	295	6.1
Receiving tubes	238	4.9
Crystals	57	1.2
	4,863	100

*From Shipments of Selected Electronic Components, 1960-1969, U.S. Department of Commerce, October 1970. Other sources may quote different figures.

is a logical, well-structured, all-inclusive system which has the further advantage of widespread use, both within the government and in industry. The SIC is intended to cover the entire field of economic activity, but in so doing, Electronic Components and Accessories (SIC 367) are represented by only five major categories, the last of which contains all components not elsewhere classified and includes such diverse products as crystals, resistors, recording heads, and pulse forming networks. Assessment of the economic impact of air pollution on such a varietal collection would seem to be difficult, if not impossible.

The classification system adopted permits simple summation of the economic effect of air pollution on each category into a value representative of the Electronic Components industry as a whole.

2.2 MAJOR ELECTRONIC COMPONENT MANUFACTURERS

Two criteria were established in selecting manufacturers to represent each component category:

- The companies selected must manufacture a determinable and statistically significant fraction of the total components in each category.
- The total number of manufacturers must be small enough to allow meaningful contacts with all of them.

Ideally, the first criterion would have been satisfied by selecting the five or six companies with the largest sales in each category. Practically, it turned out that sales figures, except those published in stockholders reports, are secrets guarded with militant zeal. Thus, an alternate approach was developed which provided a qualitative but not quantitative solution to the dilemma.

In June, 1969, McGraw-Hill polled a sampling of subscribers to Electronics magazine and asked them to indicate the names of manufacturers whose products they preferred. A listing of 192 products was provided to each subscriber who was asked to write in the names of the three manufactuers he preferred for each product and to indicate his first choice. The results were tabulated and published later in the year.[3]

In one sense, the results do nothing more than represent a popularity poll, but in a broader sense they would seem to be valid for this study. The readers and subscribers to Electronics, among whom are the authors of this report, as a group probably are a reasonably representative cross section of the electronic community. Thus, their opinions could be expected to be reflected in their buying habits and this in turn should be reflected in the sales of the companies from which they buy.

Another factor which was considered before deciding to utilize the poll was the size of the sample. Over 9,500 questionnaires were sent out; over 1,500 returns were received, thereby assuring good representation.

In consideration of these two factors, the composition and magnitude of the sample polled, we have assumed that the ranking of manufacturers based on preference would be the same as a ranking based on sales.

The Product Preference Poll (PPP) categories are not identical to the Department of Commerce (DOC) categories adopted for this study, but by simply combing appropriate PPP categories, the DOC categories were duplicated almost exactly. Proceeding in this way, we produce Table 2-2 which lists the major manufacturers of each type of electronic component.

What is needed in addition to this qualitative listing is a quantitative evaluation of how large a fraction of the total sales for each category is represented by the companies listed. Since individual company sales are unavailable, all we can say is that the companies listed probably account for most of the sales.

There are 48 companies appearing on the list, several appearing in more than one category, and each was contacted by telephone. During the interviews, other branches of the company being interviewed or other companies were sometimes suggested as sources of information. Additionally, it soon became apparent that users of electronic components and equipment were valuable sources of information. To complete the picture, several interviews were conducted with government agencies, professional associations, and university groups. All together, over one hundred interviews were conducted to obtain the data utilized in the following sections.

Table 2-2. Representative Manufacturers

Category	Manufacturer
Semiconductor devices	Motorola Texas Instruments General Electric RCA Fairchild
Integrated circuits (active)	Fairchild Motorola Texas Instruments Signetics National Semiconductor
Integrated circuits (passive)	Vector Electronics Sprague Centralab Triad Photo Circuits
TV picture tubes	RCA Sylvania National Electronics Tungsol Admiral Zenith
Capacitors	Sprague Cornell Dubilier Mallory General Electric Aerovox Erie Sangamo
Resistors	International Resistance Corp. Allen Bradley Ohmite Dale Beckman
Connectors	Amphenol Amp, Inc. ITT Cannon Cinch Electronics Elco, Inc.

Table 2-2. Representative Manufacturers (cont'd)

Category	Manufacturer
Power tubes	RCA Varian Associates General Electric Raytheon Amperex
Transformers and inductors	United Transformer Stancor Div. of Essex International Triad J. W. Miller Co. Thordarson-Meissner
Relays	Potter & Brumfield C. P. Clare Company General Electric Sigma Instruments Guardian Electric
Receiving tubes	RCA General Electric Sylvania Amperex Raytheon
Crystals	CTS Knight Inc. International Crystal Bliley Inc. Texas Crystals Peterson Radio

3. INFORMATION SOURCES

3.1 LITERATURE SEARCH

Almost everyone at one time or another has encountered air pollution. It is also true that documented evidence indicates the existence of air pollution as early as the 16th century. Thus, history and experience have combined to produce an abundance of literature on the subject which is at once gratifying in extent and staggering in magnitude. The job of perusing it, fortunately, has been simplified by several well-indexed abstract bulletins, those published by APCA and the Defense Documentation Center being of especial value.

In addition, information was obtained from the following sources:

Clearinghouse for Federal Scientific and Technical Information
Institute of Electronic and Electrical Engineers
Institute of Environmental Sciences
National Bureau of Standards
NASA Electronics Research Center Library
National Assocation of Corrosion Engineers
American Association for Contamination Control
American Society for Testing Materials

Pertinent references are included in the General Bibliography, Section 8, and an annotated bibliography of the most significant documents is contained in Section 7.

3.2 TELEPHONE INTERVIEWS AND FIELD VISITS

The background and theoretical information obtained from the literature was supplemented by conditions currently being experienced by electronic component manufacturers and users selected as outlined in Section 2. The companies and organizations actually contacted are listed in Exhibits in Section 9. Some of the names on the planned list are omitted from the tables, either because a sufficiently cognizant individual could not be contacted or because company policy forbade dissemination of the requested information. On the other hand, several companies were contacted that were not on the planned list. These were added often at the suggestion of persons being interviewed.

The 105 telephone interviews uncovered 13 companies and organizations with sufficiently interesting stories to warrant personal visits. These are indicated in the tables by an asterisk. Case histories of some of these facilities are included in subsection 4.2.

3.3 SPECIAL SURVEY OF ITT CORPORATE DIVISIONS

Within the International Telephone and Telegraph System are several companies engaged in the manufacture of six of the major components listed in Section 2. A special survey of these companies was conducted in advance of the planned survey, both to develop the interview procedure and to uncover any previously unanticipated problems. Several useful results were obtained:

- It was discovered that a telephone conversation of a few minutes could elicit a great deal more information than a written questionnaire.
- The unique story of ITT Jennings problems with the State of California was uncovered.
- The survey forewarned of the paucity of correlative data.
- The importance of long-term effects was suggested.

4. TECHNICAL ASSESSMENT OF THE EFFECTS OF AIR POLLUTION

One of the earliest laboratories providing an experimental determination of the effects of air pollution was the city of London. It was an inadvertent and unwilling laboratory, to be sure, but the effluent from every chimney in town, combined with fog and dampness, produced conditions which could be duplicated elsewhere only with the greatest difficulty and not at all on the same scale. The most noteworthy effects, of course, were those afflicting people; other effects were overshadowed by the hazards to health. Those few who ventured to theorize on the relationship between air pollution and the corrosion of metals (e.g., Davy in 1800 and deLa Rive in 1856) had no impact.

At about the turn of the century, however, the situation began to change and by 1924 W. H. Vernon, U. R. Evans and others were establishing causal and quantitative relationships between tarnishing, moisture and hydrogen sulfide.

Today, air pollution is a viable science and like other sciences, it is the subject of an extensive literature.

What was once thought to be simply explainable, the interactions between air pollutants and materials, are now recognized to be exceedingly complex. The change has arisen, at least in part, from the recognition of greater numbers of variables so that controlled laboratory experiments are difficult to perform and harder to interpret in terms of the real world. This should not be construed as an admonishment against further experimentation; on the contrary, it emphasizes the need for additional well-conceived experiments.

The analysis and experiments which have been performed so far lead to rational theories of pollution damage mechanisms, but for electronic components only two pollutants appear to be of major significance. These are particulate matter and gaseous sulfur compounds and the damage caused by the former exceeds the latter by a wide margin.

In the following sections, the general effects of air pollution on electronic components with emphasis on theoretical and observed damage mechanisms will be examined, and this will be followed by a discussion of what was actually observed in the survey.

4.1 GENERAL EFFECTS OF AIR POLLUTANTS ON ELECTRONIC COMPONENTS

Some air pollutants may attack the materials from which electronic components are made while others may affect the component as a whole. The literature abounds with studies of the interactions between various gaseous pollutants and a whole host of materials, but with only a few exceptions, studies of gross overall effects are lacking. A complete technical and economic picture must, of course, include both microscopic and macroscopic effects.

4.1.1 Theoretical and Experimental Determinations of Materials Damage Effects

Corrosion of metals may occur by reaction with gases, such as high-temperature oxidation, or with liquids. In the latter cases, metals normally go into solutions as ions, and the basic mechanism, therefore, is electrochemical. The theory is summarized by Muffley[4] and by Larrabee[5], and Evans[14] devotes an entire chapter to it.

Briefly stated, local dissimilarities on the surface of a metal will cause local anodes and cathodes to be formed in the presence of moisture. Galvanic action then proceeds in well-known ways. Sparling[6] generalizes on this theory by stating that corrosion is a frequent cause of electronic equipment malfunction and that galvanic corrosion is the factor most often blamed. Sparling is referring to the electromotive potential which results when certain dissimilar metals are in close contact in the presence of an electrolyte, and he gives tables of "couples" which should be avoided.

More specifically, many studies, both in the laboratory and in the field, have led to qualitative and quantitative understanding of how various atmospheric contaminants interact with a wide variety of materials. Many of

the materials tested are used in electronic components. Table 4-1 lists the major metallic materials used in the eleven categories of components listed in Section 2, Table 2-1. Only metals are included because the damage effects described in the literature are aimed mostly at these materials.

Table 4-1. Metals Used in Electronic Components

1. Semiconductors
   Ag, Ni, Cu, Al, Pb, Sn, Au
2. Integrated Circuits
   Same as semiconductors
3. TV Picture Tubes
   Ag, Cu, Pb, Sn
4. Capacitors
   Cu, Al, Pb, Sn, Brass, Steel, Cd
5. Resistors
   Ag, Cu, Pb, Sn
6. Connectors (including Printed Circuits)
   Ag, Cu, Al, Brass, Au, Pb, Sn, Cd
7. Power Tubes
   Ag, Cu, Pb, Sn, Au, Pd, Pt
8. Transformers and Inductors
   Cu, Fe, Al, Pb, Sn, Brass, Steel, Cd
9. Relays
   Ag, Cu, Fe, Al, Pb, Sn, Brass, Steel, Cd, Pd
10. Receiving Tubes
    Ag, Cu, Pb, Sn, Au
11. Crystals
    Ag, Cu, Al, Pb, Sn

The primary air pollutants are identified by Stern (ref. 7, p. 12) and are listed here in Table 4-2. Radioactive compounds have been specifically excluded from this study. The remainder on the list, except carbon compounds, were found to have some kind of effect on the materials from which electronic components are made.

The possible damage effects likewise have been identified and listed by Stern (ref. 7, p. 618). These mechanisms are included here as Table 4-3.

The data in Tables 4-1, 4-2, and 4-3 are combined to form Table 4-4 which shows the kind of interaction to be expected between all of the currently classified air pollutants (except radioactive compounds) and the electronic components being considered in this study. The entries in Table 4-4 consist of one or more letters, each representing one of the damage mechanisms listed in Table 4-3, followed by one or more numbers in parenthesis. The latter are references keyed to the General Bibliography, Section 8.

A few general observations are immediately obvious.

First, gaseous sulfur compounds will affect every category of electronic component, either by chemical attack from H_2S or by the sulfur acid formed from SO_2 and moisture. Judging from the amount of effort spent studying sulfur compounds, one would conclude that these gases are by far the most serious attackers. This conclusion is confirmed, in fact, by Tice[8], who states that ". . . from the standpoint of corrosion, SO_2 content is probably the most critical air pollutant."

A second general observation is that very little seems to have been done to study quantitatively the first two damage mechanisms - (a) abrasion and (b) deposition and removal. The first of these, abrasion, might not be too important because electronic components in the field are almost always protected from high velocity particles. The second, however, would seem to merit some study, because, as will be shown in the next section, the cleaning of electronic components is rapidly becoming a recognized method of maintenance. If, as suggested by Stern, cleaning of deposited material is accompanied by the removal of some base material, then there are definite limits to the number of times a component or instrument should be cleaned.

Table 4-2. Primary Air Pollutants
(From Stern, A. C., Air Pollution, Volume 1, p. 12)

1. Fine Solids (less than 100 microns)

2. Coarse Solids (greater than 100 microns)

3. Sulfur Compounds (e.g., SO_2, H_2S)

4. Organic Compounds (e.g., aromatic and aliphatic hydrocarbons)

5. Nitrogen Compounds (e.g., NO, NO_2, NH_3)

6. Carbon Compounds (e.g., CO, CO_2)

7. Halogen Compounds (e.g., HF, HCl)

8. Radioactive Compounds

Table 4-3. Air Pollutant Damage Mechanisms
(From Stern, A. C., Air Pollution, Volume 1, p. 618)

a. Abrasion

b. Deposition and removal - effect which occurs after repeated cleaning to remove deposited material

c. Direct Chemical Attacks - Example is tarnishing of silver by H_2S

d. Indirect Chemical Attacks - SO_2 may be converted to H_2SO_4 which deteriorates materials

e. Electrochemical Corrosion - Stern includes only ferrous metals in this category; we include also metal couples capable of forming galvanic cells

Table 4-4. Effects of Air Pollutants on Electronic Components*

	Semi-conductor Devices	Integrated Circuits	TV Picture Tubes	Capacitors	Resistors	Connectors	Power Tubes	Trans-formers & Inductors	Relays	Receiving Tubes	Crystals
Fine Solids (< 100 μ)						e(15)(16)		e(14)	(15)		
Coarse Solids (> 100 μ)											
Sulfur Compounds	c(15)(17)(18)(19)(20)	c(15)(17)(18)(19)(20)	c(15)(17)(19)	c(15)(17)(18)(19)	c(15)(17)(18)(19)	c(15)(17)(18)(19)(20)(22)	c(15)(17)(18)(19)	c(15)(17)(18)(19)	c(15)(17)(18)(19)(22)	c(15)(17)(18)(19)	c(15)(17)(18)(19)
	d(14)(17)(21)	d(14)(17)(21)	d(17)(21)	d(17)(21)	d(18)(19)	d(17)(21)(22)	d(17)(21)	d(4)(5)(17)	d(5)(17)(22)	d(5)(17)	d(5)(17)
Organic Compounds							d(15)				
Nitrogen Compounds									c(23)		
Carbon Compounds											
Halogen Compounds	c(4)(15)	c(4)(15)	c(4)(15)	c(4)(15)	c(4)(15)	c(4)(15)	c(4)(15)	c(4)(15)	c(4)(15)	c(4)(15)	c(4)(15)

*Lower case letters refer to the corresponding damage mechanisms of Table 4-3. Numbers in parentheses refer to the General Bibliography, Section 8.

A third observation is that the carbon compounds, CO and CO_2, cause no damage to materials. This is not surprising.

A fourth observation, not quite so obvious, is that each of the five damage mechanisms is a function of, or at least is affected by, several other factors, among which are temperature, humidity, sunlight and electric field. Thus, a true representation of what we have shown in two dimensions really requires many dimensions. This is further evidence of the complexity of the whole problem.

The major result of this survey of the literature is that the primary effect of air pollution on electronic components would be expected to come from the gaseous sulfur compounds, primarily SO_2 and H_2S. Our survey of manufacturers, however, revealed quite another conclusion.

4.1.2 Observed Damage Effects to Electronic Components

A series of telephone interviews and plant visits to manufacturers of electronic components failed to reveal the widespread effect of SO_2 and H_2S expected from the literature survey. Instead, most manufacturers disclaimed any problems with any forms of air pollution whatsoever, and for those who had experienced difficulty, the greatest offender by far was airborne particulates.

In general, particulates cause damage to electronic components in five different ways, none of which is included in Stern's list of damage mechanisms (Table 4-3). These are:

1. Interference with the photoresist process for integrated circuit fabrication.
2. Spot formation on the screens of TV and cathode ray tubes.
3. Release in vacuum of adsorbed gas.
4. Provision of microscopic leakage paths in semiconductors and integrated circuits.
5. Provision of gross current leakage paths in all electronic equipment.

It is to be noted that the first four of these mechanisms cause damage during manufacture to semiconductors, integrated circuits, TV and cathode ray tubes, and vacuum components such as vacuum capacitors, relays and tubes. The last named mechanism, gross current leakage, occurs in the field on finished products.

A sixth damage mechanism, also attributable to particulates, is not included in the list because it was noted for only a specific piece of equipment and is, therefore, a special case. Traffic controllers have rotating parts which lose their lubrication, apparently due to the capillary action of accumulated particulate matter. As noted in section 5, this effect results in a significant cost.

Most manufacturers of components subject to damage by particulates provide some degree of protection during the manufacturing process. This can vary from nothing more than the air filters in the air conditioning system to elaborate clean rooms with laminar flow. The amount of protection depends upon the component and the environment in which it is manufactured.

A note of caution is necessary in interpreting these results. Manufacturers generally do not identify the source of the particulate matter. Experience has taught them, however, that it is either airborne or human-borne and many believe that the latter may be the more prolific source.

Regardless of the source, one company, the Odell Company, has learned that accumulations of dirt in electronic equipment frequently leads to failure or malfunction and has devised a system to clean equipment. Experience has shown that this often eliminates the need for repairs or replacement of parts. The company and its system are described more fully in the section on Case Histories.

It is apparent from this survey, therefore, that particulate matter, operating in one of the five damage mechanism modes listed above, is responsible for most of the detrimental effects on electronic components. It seems plausible that many of the preventive measures first used on military equipment and later on space hardware are becoming commonplace. The document in reference 6, for example, is in essence, a design manual for the

prevention of corrosion in electronic components used by the U. S. Army. Since, as we have seen, almost all of the work in the field has been directed toward the study of corrosion, and since the preventive measures described in reference 6 likewise are aimed at reducing or preventing corrosion, it seems logical to assume that these measures have been successful and that what we are observing today are the effects which were masked by the heretofore more prevalent corrosive effects.

4.2 CASE HISTORIES

Telephone interviews with manufacturers and users of electronic components and equipment resulted in uncovering several cases directly pertinent to this study or of unusual general interest. These cases are presented here because they aid in understanding both the technical and economic problems encountered.

4.2.1 Navigational Aids Facility - FAA

The Federal Aviation Administration (FAA) operates approximately 900 Very High Frequency Omnidirectional Ranging (VOR) stations in the United States to provide navigational assistance to commercial, military, and private aircraft. These stations radiate a coded radio signal by means of which a pilot may determine his position. The VOR station located near Charleston, West Virginia is maintained by personnel who report to Mr. John McGivern. Mr. McGivern relates that in 1965 and early 1966, about one year after the equipment was installed, evidence of corrosion started to appear. The biggest problem was sulfiding of silver-plated contacts with consequent arcing and pitting to the extent that replacements were required. Fortunately, aircraft traffic delays resulting from equipment downtime were minimal because of the redundancy built into the VOR system.

The two main sources of corrosive agents in the Charleston River Valley were the many chemical plants that emitted a variety of substances, including gaseous sulfur compounds, and a nearby municipal burning dump that produced all combustion products.

The solution arrived at by the FAA was to install an air-conditioning system with special activated-charcoal filters to eliminate pollutants. This was

done late in 1966 at an approximate cost of $6,500. Corrosion appears to be under control at this time.

4.2.2 Weather Radar - U. S. Weather Bureau

The U. S. Weather Bureau operates approximately 40 type WSR-57 weather radar stations in the United States for the purpose of accumulating data concerning storm systems in the area. One of these radars has its antenna, transmitter, and receiver mounted on a chimney of a power plant at the University of Chicago. This radar is maintained by personnel who report to the area Engineering Manager, Mr. Harold Anderson, in Kansas City, Missouri. Mr. Anderson related that this radar equipment was exposed to high concentrations of SO_2 and particulates from the stack for several years. The equipment became very dirty and its appearance deteriorated greatly. The structural tower supports corroded sufficiently to cause the weather bureau to call in a structural consultant to check the integrity of the tower. The tower was deemed structurally sound and the equipment still functioned normally. A check of maintenance records revealed that electronic component failures for this equipment were no greater than for identical equipments in locations like Wichita, Kansas, and Missoula, Montana, which have low pollution levels (these sites are not near local sources of pollution).

It would appear from this case that the weather radar equipment is relatively immune to attack by air pollution. This is not all surprising because most of the components in this radar are hermetically sealed against humidity and this also affords protection against attack by air pollutants.

4.2.3 Telephone Switching Equipment - N. Y. Bell Telephone Co.

The New York Bell Telephone Company operates a number of central telephone switching centers in New York City. These switching centers contain complex electronic switching networks, many of which are computer-controlled. In 1965, one of these centers, which was approximately five blocks away from a power-generating station, was exhibiting erratic computer behavior. IBM engineers were called in to evaluate the situation.

IBM claimed, according to Mr. E. P. Hodges, New York Bell Telephone Buildings Engineer, that the computer was suffering from outside particulate contamination and recommended that all intake air for the installation be filtered.

A high-efficiency (approximately 85%) deep-bed air filter was developed for this use and placed in series with a coarse prefilter for removal of large particles, bugs, etc. The installation of this filter eliminated the computer malfunctions and decreased maintenance to other switching equipment. Over the next few years this type of filter system was installed in all New York central switching buildings. The company estimates that the initial cost was approximately 1% of the cost of the air-conditioning system.

4.2.4 Precision D-C Motors - Western Gear Company

The Western Gear Co. manufactures a line of very high reliability precision d-c motors for Sandia Laboratories. These motors must tolerate several years of storage at temperatures of 225°F; then they must start immediately and run at 15,000 rpm. These motors are built in an ultra-clean facility that uses banks of High-Efficiency Particle Air (HEPA) filters in a recirculated-air system. In addition, this type filter cleans outside air used for down-draft cleaning stations.

The filters are changed when the particulate buildup in the filter causes a pressure drop which exceeds a predetermined value. According to Mr. C. W. Yost, one of Western Gear's product managers, the first set of down-draft filters was replaced after 1-1/2 years of operation. The second set became clogged with dirt in approximately 4 months. The dirt in these filters was analyzed and found to have a high iron content. The source of this dirt was traced to a construction site where an excavation was being made for a school building. The company estimated that the cost of premature replacement of these filters was $3,000.

4.2.5 Integrated Circuits

The manufacture of semiconductor devices and integrated circuits relies heavily on photographic processes to delineate the areas on the surface

of a silicon chip into which carefully controlled contaminants (dopants) are diffused. One of the key steps in this process is the application of a photo-resist material to the wafer surface. This photo-resist material is a cross-linked organic polymer that is relatively insoluble in the washing solution until exposed to ultraviolet radiation. After certain areas of the wafer surface are exposed to a controlled ultraviolet source through a precision mask, the photo-resist polymer is broken down by the photochemical action (breaking of cross-link bonds). Both the exposure time and wavelength of the ultraviolet radiation are critical in preventing additional cross-linking from occurring and producing changes in the characteristics of the photo-resist material.

In 1963 and 1964, engineers at the Fairchild Company discovered that during certain times of the year and at certain times of the day, an insoluble scum or film would remain on the silicon wafer after the washing operation even though all precautions were taken. This film would prevent diffusion of dopants and interfere with adhesion of deposited metal conductors. In some cases, it appeared that the areas that were intended to be unexposed actually had been partially exposed. These effects led to unacceptably poor quality in the final devices.

It was suspected that these effects were related to photochemical oxidants present at certain times in the atmosphere. Qualitative correlations were established between "smoggy days" and poor yield from the photo-resist operations. Some experiments were conducted by performing resist operations utilizing a dry nitrogen atmosphere into which small amounts of ozone were injected. When pure nitrogen was used, no film formed and no problem existed; when ozone was injected, film formed with the attendant problems.

It was deduced that the photochemical oxidants were creating additional cross-linking in the exposed photo-resist material, producing an insoluble polymer. In the case of the unexposed material, it was assumed that the oxidants were creating the same effect as exposure to ultraviolet radiation, i.e., breaking cross-link bonds.

From this point on, solution to the problem took different forms in different branches of the semiconductor industry. Some companies chose to use different types of photo-resist materials which were immune to attack by

oxidants, while some resorted to air cleaners and use of dry nitrogen atmospheres.

The modified types of photo-resist material proved to be more difficult to process and handle, since they had a high solid content and required more filtering. These materials also required more closely controlled ultraviolet wavelength and higher intensities.

The Signetics Company chose to utilize carbon filters in conjunction with water screens or scrubbers to remove these damaging oxidants from plant intake air, and the use of dry nitrogen atmospheres in critical assembly areas. The estimated maintenance costs of the air-cleaning system were $30,000 (7.5 million cubic feet per month). Approximately 30% of the nitrogen is used in the photo-resist operation.

4.2.6 Vacuum Components - ITT Jennings

The Jennings Radio Manufacturing Corporation, a subsidiary of the International Telephone and Telegraph Corporation (ITT), operates a facility which manufactures high-voltage vacuum capacitors, switches and relays at San Jose, California. These components depend on a hard vacuum to operate properly, and are adversely affected by contamination of all types. They are particularly affected by particulates that become lodged within the vacuum envelope and which, subsequent to vacuum pumping, outgas and produce a conductive atmosphere within the device.

In the fall of 1967, Jennings learned that the State of California was planning to condemn a portion of its property for construction of a freeway ramp approximately 400 feet from their main manufacturing building. Jennings became concerned about the possibility of contamination from construction and use of the freeway, and instituted a study program to determine whether the effects would be sufficiently deleterious to warrant a counter-suit against the condemnation.

Jennings was not able to delay the freeway, but the company engaged a consultant who measured particulate levels at strategic locations within the plant, both before and after construction was started. Significant increases

were noted at all monitor stations. Thus, Jennings was faced with increased rejection rates for its sensitive components or an immediate expenditure to control the added dust and dirt.

Choosing the latter course, the company expended approximately $50,000 for upgrading air handling systems, providing entrance protection, sealing windows and doors, installing additional air handling equipment in some locations, and providing more efficient filters. In addition, the company estimates that its annual costs for equipment maintenance and added janitorial services amount to $20,000.

4.2.7 Instrument Cleaning - M. P. Odell Company

The M. P. Odell Company started business in 1947 as a manufacturer's representative. The company established a service department with facilities for calibrating both a-c and d-c instruments, and quickly noted that a large number of instruments being returned from the Akron, Ohio, area were inoperative simply because of a black deposit on silver switch contacts. The black deposit, although never identified formally, was attributed to the presence of sulfur gas arising from the numerous rubber and tire factories in the Akron area. This was the company's first hint that air pollution could cause malfunctioning in electronic instruments.

Later, in the 1960's, Odell began receiving inoperative or unstable instruments in which no defective parts could be found. The company cites one early experience of an FM tuner which was drifting so badly that it was useless. Cleaning was the only thing necessary to restore it to its original factory stability.

Mr. Odell then conducted further tests and experiments which convinced him that a major cause of instrument instability or malfunction was accumulations of dirt and grime which caused current leakage paths. Additional experimentation led to the adoption of a solution of detergent in water as the ideal cleaning agent. A chemist was engaged to develop a detergent formula which, in addition to being a good cleaning agent, would also be non-toxic, non-dermatologic, non-explosive and biodegradable. The presently used solvent was the result.

A cabinet equipped with a turntable, lights, a spray gun for applying the solvent and rinse water, and an air hose, plus a temperature-controlled drying cabinet, completes the system.

In the four years since starting manufacture of its cleaning systems, the company has encountered many examples of the deleterious effects of any contaminants which can settle or condense on electronic components in such a way as to cause leakage paths. It has been observed that the most common offenders appear to be tobacco smoke and dust, although special conditions have been encountered under unique circumstances. The Jones and Laughlin Steel Company, for example, operates oscillographs in an atmosphere apparently laden with iron oxide and cutting-oil vapor. This particular combination rapidly degrades the performance of the instruments, but fortunately, the dirt yields quite readily to the cleaning process.

The Magnavox Company utilizes approximately 30,000 instruments of various kinds in its daily operations, and while the operating environment is not unusually dirty, a regular routine for cleaning all instruments several times a year has been established. Other companies are apparently establishing similar procedures.

The total annual cost of cleaning instruments may be estimated as follows:

We know from data supplied by the M. P. Odell Company that approximately one million instruments now go through their cleaning systems each year. Since many instruments are cleaned routinely several times per year, we can estimate that the one million cleanings represent, conservatively, 250,000 instruments.

We use values of 50 cents per cleaning for the cleaning solution and one-half hour per cleaning for labor. The latter figure includes time for disassembly and reassembly, as well as the actual cleaning. Both figures were supplied by Odell. Assuming a value of $5 per hour for labor, we arrive at the total cost for one million cleanups of $3 million.

There is no way of determining accurately how much of this cost is attributable to air pollution, but from information supplied by Odell about the environments in which typical instruments are located and the type of contaminants encountered, we would estimate that at least two-thirds of the costs are related to air pollution.

4.3 STATISTICAL OBSERVATIONS

In the preceding two sections, the damaging effects of air pollutants on the materials composing electronic components was examined from theoretical and experimental considerations as discussed in the literature and these results were compared with field experiences. To complete the picture, it would be desirable to correlate equipment failure rates (or some similar index of malfunction) with pollutant levels. As may be surmised, data of this nature do not seem to exist. People who keep records on failure rates of their equipment do not have air quality measuring equipment and vice versa.

Lacking specific data of the kind required, but having available failure rate data from both the Federal Aviation Authority and the Weather Bureau, along with air quality data from EPA, an attempt was made to establish a correlation.

The air monitoring stations from which data were used were always located in the same city as either the VOR or Weather Bureau stations, but not necessarily as near as would be desired. Thus, this was in the nature of an experiment more than anything else, and as experiments are sometimes inclined to do, this one produced negative results.

The following paragraphs describe the method of analysis and the results obtained.

4.3.1 Methods of Analysis

Since failure of electronic components and equipment involve many environmental and other variables, and since the problem is in part one of statistical failure analysis, multivariable analysis is an appropriate research method for examining this problem. Computer methods are essential, even considering the amount of data involved with this effort. The computer

employed was the ITT-EPL IBM 1130. In particular, multiple regresion analysis patterned after the methods of Ezekiel and Fox[9] and Sprent[10] was used.

The basic data comprising this study were mean annual concentrations of the three pollutants (suspended particulates, sulfur dioxide, and nitrogen dioxide), taken from 1966 NAPCA air quality data[11], and failures of electronic equipment taken from FAA and U. S. Weather Bureau data.

4.3.2 Navigational Aids

The FAA operates approximately 900 VOR systems in the U. S. for use by aircraft pilots in establishing their position. These systems basically consist of signal generation and coding circuitry and transmitter modules. Data regarding failure of these VOR stations are gathered and compiled by the System Maintenance Service Branch of the FAA. The data are coded so that failures due to electronic equipment are identified for each station. Data for fiscal years 1966 and 1967 were used and covered all VOR electronic equipment failures from July 1965 through June 1967. These data were compared to air quality data for 1966.

The first sample utilized data from the seven cities identified in Table 4-5.

The regression analysis was carried out utilizing the three pollutant concentrations as the independent variables X_1, X_2, X_3 in the regression equation below. X_4, the dependent variable, was VOR failures.

$$X_4 = A_o + B_1X_1 + B_2X_2 + B_3X_3$$

The regression coefficients Bi and correlation coefficients Ri4 are given below:

Variable	Mean Value	Std. Dev.	Correlation Ri4	Regression Bi
X_1 Particulate level	132.7	27.60	0.661	0.084
X_2 SO_2	117.5	80.76	-0.132	-0.018
X_3 NO_2	196.8	109.7	-0.058	0.012
X_4 VOR failures	5.28	2.19		
Intercept A_o	-6.16			
Multiple correlation coefficient	0.78			

In order for a correlation between two variables to be considered significant (i.e., reason exists to doubt the independence of the two variables), it must exceed standard values for a given sample size. These values from ref. (9) for a number of sample sizes N and confidence levels r are given in Table 4-6.

It can be seen that correlation coefficient between particulates and VOR failures of 0.661 does not exceed the 95% value of 0.669 from Table 4-6, but is sufficiently close to indicate a possible trend. There is no apparent correlation in this sample with either of the gaseous pollutants. A second, larger sample of 31 cities was chosen as indicated in Table 4-7.

Applying the same analysis to these data yielded the following results:

Variable	Mean Value	Std. Dev.	Correlation Ri4	Regression Bi
X_1 Particulates	128.4	33.07	0.080	0.015
X_2 SO_2	70.00	74.50	0.031	-0.007
X_3 NO_2	140.1	73.61	0.244	0.015
X_4 VOR Failures	4.58	3.22		
Intercept A_o	0.963			
Mutiple correlation coefficient	0.307			

Again, by comparing these correlation coefficients with those of Table 4-7, it is found that none is significant at the 95% confidence level.

One may conclude from the results of these rather limited samplings of navigational aids failures that there is no significant correlation with the air pollutants considered.

The author wishes at this point to acknowledge the cooperation and assistance provided by the System Maintenance Services Division of the FAA, and in particular by Mr. Ed Kaneko.

4.3.3 Weather Radar

The U. S. Weather Bureau operates approximately 40 weather radars in the continental United States. These S-band radars have both transmitter and

Table 4-5. Electronic Equipment Failures at Seven VOR Stations

Location	Annual Failures	Pollutant Concentration $(\mu g/m^3)$* Susp. Part.	SO_2	NO_2
Denver, Col.	5	126	18	68
Cincinnati, Ohio	8	154	44	234
Chicago, Ill.	5	124	221	333
St. Louis, Mo.	2	143	132	89
Philadelphia, Pa.	6	154	225	288
Washington, D. C.	2	77	90	271
Pittsburgh, Pa.	9	151	93	95

*Arithmetic mean of 26 randomly selected 24-hour ~~bubbler~~ samples collected over a one-year period.

Table 4-6. Standard Correlation Values

N	$\gamma.95$	$\gamma.99$	$\gamma.995$
5	.805	.934	..959
7	.669	.833	.875
10	.549	.715	.765
20	.378	.516	.561
30	.306	.423	.463
50	.235	.328	.361
100	.165	.232	.256
1,000	.052	.062	.081

Table 4-7. Electronic Equipment Failures at 31 VOR Stations

Location	Annual Failures	Annual Mean Pollutant Concentration ($\mu g/m^3$) Susp. Part.	SO_2	NO_2
Washington, D. C.	2	77	90	271
Pittsburgh, Pa.	9	151	93	95
Baltimore, Md.	3	144	107	75
Nashville, Tenn.	8	115	29	65
Buffalo, N. Y.	1	139	25	169
Chattanooga, Tenn.	4	140	34	66
Cleveland, Ohio	14	116	78	191
Charleston, W. Va.	5	226	29	68
Cincinatti, Ohio	8	154	44	234
Dayton, Ohio	4	143	49	78
Dubuque, Iowa	9	132	16	189
Denver, Colorado	5	126	18	68
Des Moines, Iowa	0	123	13	82
El Paso, Texas	7	193	63	73
Hartford, Conn.	7	90	62	161
Indianapolis, Ind.	4	154	54	103
New York City	1	134	346	228
Louisville, Ky.	2	129	38	175
Kansas City, Mo.	4	116	12	136
Milwaukee, Wisc.	0	150	28	142
Marlton & Mville, N. J.	5	98	42	186
Minneapolis, Minn.	4	87	44	112
Oklahoma City, Okla.	7	107	10	201
Chicago, Illinois	9	124	221	333
Portland, Oregon	1	75	22	62
Providence, R. I.	3	121	125	99
Philadelphia, Pa.	6	154	225	288
Seattle, Wash.	7	76	35	93
Salt Lake City, Utah	2	93	20	109
St. Louis, Mo.	4	143	132	89
Youngstown, Ohio	2	152	66	105

receiver mounted with the antenna on a tower exposed to the outside environment. The balance of the components making up the weather radar (data processing, display, and communications) are located inside in an air-conditioned environment. Maintenance and component failure data for these radars are filed on computer tape for ready retrieval. Component failures are identified as to which portion of the radar they came from. If there are any significant effects of air pollution on the electronic components used in this radar, one would expect higher failure ratios for those components in non-air conditioned areas. Component failure data for calendar year 1966 and air quality data for the same locations are presented in Table 4-8.

Multiple regression techniques were applied to total component failure data:

Variable	Mean Value	Std. Dev.	Correlation Ri4	Regression Bi
X_1 SO_2	87.16	103.00	0.186	0.118
X_2 NO_2	169.00	88.25	-0.056	-0.155
X_3 Particulates	126.33	26.19	-0.641	-0.757
X_4 Component failures	48.66	23.45		
Intercept, A_o	160.33			
Multiple correlation	0.819			

Note that none of the Ri4 are significant at the 95% level when compared to Table 4-6 except for the seeming negative correlation between suspended particulate matter and component failure. At this time there is no readily available physical interpretation for this result. Possibilities include such things as a higher level of preventive maintenance in areas where particulate levels are high. This possibility could not be confirmed by discussion with Weather Bureau personnel.

Table 4-8. Weather Radar Component Failures

Location	Annual Component Failure Total	Annual Component Failure Non Air-Cond.	Pollutant Concentration ($\mu g/m^3$) SO_2	Susp. Part.	NO_2	Susp. Part.
Buffalo, N. Y.	25	1	25		169	139
Cincinnati, Ohio	20	13	44		234	154
New York, N. Y.	77	13	346		228	134
Pittsburgh, Pa.	30	15	93		95	151
Washington, D. C.	46	16	90		271	77
Oklahoma City, Okla.	60	9	10		201	107
Chicago, Ill.	39	12	221		333	124
Desmoine, Iowa	51	17	13		82	123
Detroit, Mich.	25	11	16		78	161
Kansas City, Mo.	77	11	12		136	116
Minneapolis, Minn.	92	24	44		112	87
St. Louis, Mo.	42	8	132		89	143

The regression analysis was repeated for the same location using only component failures in non-air-conditioned areas. The results are:

Variable	Mean Value	Std. Dev.	Correlation Ri4	Regression Bi
X_1 SO_2	87.16	103.00	0.030	0.013
X_2 NO_2	169.00	84.25	-0.073	-0.025
X_3 Particulates	126.33	26.19	-0.470	-0.129
X_4 Component failures	12.41	5.64		
Intercept A_o	31.79			
Multiple correlation	0.563			

Again, none of Ri are significant at the 95% level except for the negative correlation with suspended particulates. While this value decreased, it is still not explained.

The seeming immunity of weather radar components to air pollution suggested by this analysis is borne out as indicated by further discussion with Weather Bureau personnel. These discussions (paragraph 4.2.2) revealed no higher failure rates in Chicago (high SO_2 level) than in rural areas.

The author wishes to acknowledge the cooperation and assistance provided by Mr. Russell Hovey of the U.S. Weather Bureau.

4.3.4 Conclusions

Although the results of the data analysis for both the VOR and Weather Bureau Stations lead to the conclusion that no valid correlation exists between equipment failures and pollutant levels, two factors mitigate the validity of this conclusion.

First, of course, is the size of the sample. Using the VOR case as an example, it may be seen by reference to Table 4-6 that a sample-size approaching 1000 would be necessary to establish 95% confidence in the magnitude of the correlation coefficients calculated. The negative coefficients obtained from the Weather Bureau calculations are quite another matter and

do not lead to the same quantitative conclusion, although qualitatively the same argument can be made. In any event, the small sample in both cases casts some doubt on the validity of any correlation or lack of it.

Second, air monitoring stations from which data were used were not necessarily located in proximity to either VOR or Weather Bureau stations, even though the city was a common factor in all cases. Air monitoring stations frequently are located in downtown areas, weather bureau stations at local airports and VOR beacons several miles from the town. Thus, there is no assurance that the air monitored by the air station is the same quality air experienced by either the Weather Bureau equipment or the VOR beacons.

While no valid conclusions can be drawn from these calculations, they do suggest an approach to obtaining valid data. Simply locate air monitoring equipment close by the electronic equipment in question and measure air quality and failure rates for periods of several months to a year or more. This could be done quite economically by utilizing mobile laboratories.

5. ECONOMIC ASSESSMENT OF THE EFFECTS OF AIR POLLUTANTS

5.1 THE COST OF MISSING INFORMATION

The ubiquitous effects of air pollution ultimately manifest themselves in our pocketbooks and yet we have only vague notions about what the effects really cost us.

The main reason for this state of affairs seems to be that the costs attributable to air pollution are not separable from other costs. Manufacturers of electronic components known to be sensitive to airborne contaminants generally filter the air entering manufacturing areas, and for some especially sensitive components, operations are conducted in clean rooms. These measures provide protection against particulate matter, but whether they are borne by some other mechanism, such as humans, is not known in most cases, nor do most manufacturers believe the distinction is important because they would take the same precautions under any circumstances. As one manager put it, he would build his plant the same way even if it were to be located in the cleanest spot on earth.

On the other hand, the Manager of Manufacturing Engineering of a large semiconductor plant stated that he had expended about $1 million (not at his present plant) to get class 100 air, only to discover that the amount of particulate matter in the building was not reduced appreciably, and moreover, that it varied with the particulate concentration in the outside air. He concluded, therefore, that dust and dirt were being brought into the building by his own personnel. Consequently, air filters were installed at each sensitive work station, positive pressure ventilation was provided, and rugs were placed at all building entrances.

Here was a case where contamination, initially thought to be air pollution, provoked a million dollar investment which turned out to be needless.

Thus, it seems that manufacturers have no other choice than to take the maximum practicable precautions against air pollution, simply because they cannot separate the effects of airborne contaminats from others.

Whenever these effects are separable, however, we see that it may be possible to achieve better results at lower cost. Another factor which would seem to contribute to lower costs, but for which data are lacking, is the effect of contaminant concentration on component damage. Nowhere in this study did we encounter anyone who could correlate contaminant concentration with rejection rates or failure rates or maintenance costs, and yet it seems intuitively obvious that to provide more protection than necessary is to incur an unnecessary expense.

Thus, these two bits of missing information, (1) separability of airborne contaminants from others and (2) relationship between concentration and damage effects, may be costly. In addition, the absence of them has a profound effect on the economic analysis that follows.

5.2 BASIS OF ECONOMIC ANALYSIS

A study of the costs of air pollution has recently been published by Ridker.[12] We have adopted the general approach to the problem discussed in his Introduction, but have arrived at a somewhat different expression of costs. Where Ridker seems to express the point of view of the economist, we have tried to look at the picture through the eyes of a manager who has responsibility for the quality of his product. His purpose, and the purpose of the sections which follow, is to determine how much air pollution actually costs him, so that he can take the most effective steps toward minimizing the costs. With this approach in mind, we identify three major cost categories (instead of Ridker's two). Thus:

C_L = Loss Cost - if nothing is done to control or abate air pollution effects, components are degraded and may ultimately fail. C_L represents the cost to the manufacturer of components lost through air pollution damage and may include secondary losses as well; that is, cost of equipment which fails because of air pollution-damaged components.

C_P = Prevention Costs - costs of installing filters, scrubbers, clean rooms, etc., necessary to provide uncontaminated air to the manufacturing area. Costs of design changes and of special materials necessary to prevent or abate the effects of air pollution should be included in this category, but as a practical matter are not because they cannot be identified uniquely.

C_M = Maintenance Costs - costs to remove the effects of air pollution once they have contaminated a component may be incurred in the factory or in the field.

The manager is presented with the problem, in principle at least, of selecting which of the three alternative costs, or combinations of them, to incur. He may decide, for example, to do nothing and simply accept the costs of the failed components. This he might do if these costs were demonstratively lower than the cost of installing control equipment, but in this case, he would doubtless rely upon the Air Pollution Control Office of the Environmental Protection Agency to take some positive steps, or he might be able to consider some litigation if he can identify the source of the offending pollution.

Obviously, he also has many other strategies available to him. What he needs is a system for expressing all of these costs which will allow him to select a strategy for minimizing his costs. The following formulation was developed with this idea in mind and, at the same time, it was intended to serve as a vehicle upon which to base an estimate of total costs.

$$\text{Let } E = E_1 + E_2 + - - - E_n = \text{set of electronic components} \quad (1)$$

$$P = P_1 + P_2 + - - - P_m = \text{set of pollutants} \quad (2)$$

Then

$$D = \sum P_i \lambda_{ij} E_j = \text{number of components damaged by all pollutants} \quad (3)$$

where λ_{ij} = probability that i^{th} pollutant will damage j^{th} component. The probability, λ, is some function of the concentration of air pollution, but as we have seen in the section on damage mechanisms, no rigorous relationship yet exists. The best we can do at the present time is to say that as the concentration of air pollutants increases, the probability increases that components will be damaged.

Returning now to costs, we see that as preventive measures are installed, then losses ought to be reduced by some amount. Similarly, cleaning or otherwise removing the effects of air pollution also ought to reduce losses. This can be represented as

$$C_T = C_P + C_M + \left[C_L - f(C_P) - f(C_M) \right] \quad (4)$$

or the total cost of the effects of air pollution (C_T) is the sum of the cost to prevent it (C_P) plus the cost to remove the effects (C_M) plus the loss cost (C_L) reduced by the amount of the loss saved by preventive and maintenance measures ($f(C_P)$ and $f(C_M)$. The loss cost may be further represented by using Equation (3)

$$C_L = cD = c \sum Pi \ \lambda_{ij} E_j \tag{5}$$

where c is the unit cost of the component in the set E.

At one extreme, if no preventive or maintenance measures are taken, then

$$C_T = C_L \tag{6}$$

At the other extreme, if preventive and/or maintenance measures are taken, then C_L may equal 0, but C_P and C_M are large, and C_T is also large. The equation, therefore, has a minimum somewhere between the two extremes, but a quantitative determination of it depends upon quantitative knowledge of the functions $f(C_P)$ and $f(C_M)$. On the other hand, Equations (3) and (4) depict an approach to minimizing air pollution costs and, at the same time, they provide a basis for a discussion of the actual costs that were uncovered during this survey.

5.3 COST ASSESSMENT AS DETERMINED BY THE SURVEY

In the preceding section, the total cost was represented by three terms, one of which, the loss cost C_L, varied inversely with the preventive and maintenance costs. While this approach shows the interrelation of all costs, another form seems more suitable for measurements. We define a residual cost C_R as cost of those components still lost, even after preventive and maintenance measures have been taken

$$C_R = C_L - f(C_P) - f(C_M) \tag{7}$$

The total cost now becomes

$$C_T = C_P + C_M + C_R \tag{8}$$

Each of the three quantities on the right can be measured, at least in principle. Since C_R varies inversely with both C_P and C_M, however, any measurements of C_R must be interpreted with caution.

5.3.1 Semiconductors

Without exception, semiconductors are manufactured in controlled atmospheres, provided either by clean rooms or filters, but in no case were these installed exclusively to control air pollution. Most manufacturers seemed more concerned about human-borne dust and dirt--hence, the clean rooms--and one manufacturer supplies filtered air at each work station, again primarily as a safeguard against human-borne contamination. Preventive costs, therefore, are low.

These devices do not lend themselves to cleaning or otherwise removing the damage effects, and one manufacturer stated that no devices returned from the field had failed due to air pollution. Maintenance and residual costs likewise are low.

5.3.2 Integrated Circuits

Some years ago, a major manufacturer of integrated circuits discovered that airborne photo-chemical oxidants could corrode the photo-resist material used in the manufacturing process (paragraph 4.2.5). Subsequently, other types of photo-resist material were developed which were less sensitive to oxidants, but which were much more difficult to apply. Thus, the choice lies between using the old material and scrubbing the incoming air, or using the newer material and accepting higher manufacturing costs. The one company for which cost data are available has adopted the first approach and estimates that it expends approximately $30,000 per year to provide scrubbed and filtered air. In addition, the company expends approximately $130,000 per year for high purity dry nitrogen, which it supplies to critical assembly and fabrication areas. We estimate that 1/3 of the nitrogen cost, or about $43,000, actually goes for abating the effects of air pollution, while the remainder must be attributed to the abatement of contamination from other sources. In 1969, this company's sales were about $40 million.* Thus $\frac{30,000 + 43,000}{40 \text{ million}} \times 100 = 0.18\%$ of the company's gross sales were expended for air pollution abatement. Extending this figure to the remainder of the $750 million integrated circuit market we arrive at $1.36 million as the cost of abating air pollution for this segment of the market.

*Source: Electronic News

No maintenance costs are incurred, since the integrated circuits do not lend themselves to this sort of treatment. Of the approximately 20% which are rejected after manufacture, at least half fail because of some form of contamination, but there the company doubted that any of this was due to air pollution. We have attributed no residual cost to air pollution.

5.3.3 Television Picture Tubes

The effect of particulate matter upon the screens of television picture tubes invariably is catastrophic and all manufacturers take special precautions to eliminate all dust and dirt from the screening areas. The source of the contamination, however, turns out to be mainly in-plant and human-borne, so the precautions take the form of protective clothing, work stations with a supply of clean air and other similar measures, none of which can be assigned primarily to the abatement or control of air pollution.

In use, television picture tubes sometimes develop leakage paths due to accumulations of airborne oily dirt. This substance, which degrades the operation of the tube, and the entire television set for that matter, can be removed by cleaning. These maintenance costs are included in paragraph 5.3.13.

There are, however, some tubes which fail in the field, and of these, some failures almost certainly are attributable to air pollution. Thus, there probably is a residual cost associated with this category, but we have no data and no means of estimating it.

5.3.4 Capacitors

Without exception, capacitor manufacturers interviewed took no special measures to control air pollution. Almost all factories are air-conditioned and this seemed to provide sufficient filtering for all purposes. We could find no preventive, maintenance or residual costs.

5.3.5 Resistors

The comments noted in the previous section can apply to resistor manufacturers also. Most plants are air-conditioned but no other precautions

are found necessary. We could find no preventive, maintenance or residual costs.

5.3.6 Power and Special Purpose Tubes

Included in this category are a wide variety of electron tubes, each of which seems to have a special problem connected with it. Oxide-coated cathodes, for example, are harmed by particulates and high humidity. Similarly, particulates are extremely damaging to x-ray image intensifiers, Plumbicons and others. Tubes with silver-plated parts are susceptible to tarnishing from H_2S. No company, however, could associate any of these damaging contaminants with their present location and experience.

On the other hand, one company, formerly located in Newark, New Jersey, found it necessary to install an electrostatic precipitator to obtain sufficiently high quality air for its manufacturing process. Since moving to a more suburban location, the problem has disappeared, and we are led to suspect that there may still be others who may be experiencing similar difficulties.

Since we did not discover any such companies, however, we conclude that if they do exist, they must represent only a small fraction of manufacturers in this category and so we attribute no preventive costs to air pollution.

Maintenance costs for cleaning are included in paragraph 5.3.13, and we believe residual costs to be vanishingly small.

5.3.7 Connectors

The contaminants most damaging to connectors, and this category includes printed circuit boards, are gaseous sulfur compounds, either as SO_2 or H_2S which react with copper and silver to form non-conducting films. To prevent these damaging effects, exposed metallic parts are gold-plated. One company expends $800,000 per year for gold and estimates that the connector industry as a whole may expend $10 million per year. Of this, we estimate that 75% may be attributed to air pollution, with the remainder being used to protect against finger marks, salt spray and other corrosive agents not associated with air pollution. The preventive cost for the industry is thus about $7.5 million.

In a study on the economic effects of air pollution on electrical contacts,[13] the Stanford Research Institute assigned a value of $20 million per year for precious-metal plating. This includes not only connector contacts, but also relay contacts and all others. We assume, therefore, that our value is contained in the $20 million figure and have not duplicated the value in our summary.

Connectors easily collect airborne dust which forms extraneous leakage paths. This is removable, however, and the concomitant costs are included in paragraph 5.3.13. We have identified no residual costs.

5.3.8 Transformers

Transformers are not at all affected by air pollution during manufacture. Bushings and insulators can develop leakage paths due to the deposition of particulates on them, but this is easily removed by cleaning. Maintenance costs are included in paragraph 5.3.13. No residual costs have been identified.

5.3.9 Relays

Experience in the manufacture of relays varies from one company which stated that the only problems were internal, and indeed, did not even provide air conditioning, to another which stated that all relay manufacturers face a constant battle with the effects of contamination on contacts. The latter manufacturer and others gold-plate relay contacts. The cost of this operation is included in the SRI study[13] referenced in paragraph 5.3.7 and is not duplicated herein. Maintenance costs are probably low, but relay contacts can become corroded and non-conductive if exposed to contaminants like SO_2 and H_2S. Replacement of defective relays should be included as a residual cost but we have no data to ascertain its magnitude.

5.3.10 Receiving Tubes

In general, air pollution does not add significant costs to the manufacture of receiving tubes. One manufacturer in the San Francisco Bay area believes that H_2S from the Bay may be causing some sulfiding of

silver contacts. Another in Connecticut has also experienced some isolated problems with the formation of silver sulfide. The number of tubes involved, however, and the costs, while not known, are probably insignificant. Maintenance and residual costs also should be vanishingly small for receiving tubes.

5.3.11 Crystals

The crystal manufacturers interviewed adopt no special precautions to abate or control air pollution. All costs related to air pollution are insignificant.

5.3.12 User Costs

Quite apart from air pollution costs incurred by the manufacturers of electronic components are the costs which the user must absorb. Two examples in this category are traffic signal controllers and telephone switching centers. Both types of equipment are degraded by particulate matter. In the first case, no preventive measures are possible since the equipment is located out of doors, hence, cleaning is resorted to as a remedy. In the second case, high efficiency air filters have been installed.

The Washington, D.C. highway department has estimated that the 1085 traffic light control systems in the District of Columbia each require 2 hours of maintenance per year. At least 50% of this maintenance is for cleaning of accumulated particulate matter which tends to interfere with proper operation of lubricated electro-mechanical components such as power contactors and timing motors. At a cost of $5.00 per hour for maintenance, this represents an estimated annual cost of $5,400 to the D.C. Highway Department for cleaning traffic light controllers, a unit cost of about $5.00 per controller.

The annual mean suspended particulate level in Washington, D.C., 77 $\mu gm/m^3$, is less than the national average of 102 μ gm/m^3 for all U.S. urban areas. We assume, therefore, that other areas, on the average, will find it necessary to maintain their controllers with at least the same frequency as Washington. A simple extrapolation to the 244,500 traffic signals in the U.S., most of which are in urban areas, yields a total annual maintenance cost of about $1.2 million.

The New York Bell System has been forced to install high-efficiency air filters in all of its New York City switching centers, and these, of course, must be maintained. New York Bell estimates that switching centers in the borough of Manhattan alone use 15,000 tons of air-conditioning, and that initial filter cost represents about 1% of the cost of this air conditioning. Cost of commercial air conditioning equipment is estimated at approximately $500 per ton. This results in an initial cost for air filtering of $5.00 per ton or $75,000 for Manhattan, an annual cost of $7,500, since the amortization period is 10 years. New York Bell estimates that filter maintenance in a building requiring 2,000 tons of air conditioning takes two men 15 days every 6 months, or 60 man days per year. Assuming $5.00 per hour, the filter maintenance labor per ton of air conditioning is

$$\frac{60 \times 8 \times 5}{2000} = \$1.20 \text{ ton}$$

or $18,000 per year in Manhattan. Filter replacement materials cost $10.00 for 4 square feet of filter element. Total filter replacement costs can be calculated by assuming 400 cubic feet per minute of air per ton of air conditioning, and an output velocity of 1,000 linear feet per minute. This leads to a duct cross section of 0.4 square feet per ton of air conditioning. At $2.50 per square foot, the cost for filter materials is $1.00 per ton of air conditioning. This figure leads to a total filter replacement cost of $30,000 per year in Manhattan.

In summary, the costs to the New York Bell System to prevent the damaging effects of air pollution to approximately 1.47 million telephones in Manhattan are estimated to be:

Equipment Amortization	$ 7,500
Yearly Maintenance Labor Cost	18,000
Yearly Filter Material Cost	30,000
Annual Cost	$55,500, or $0.0378/telephone

Manhattan is like no other city, of course, but it seems safe to assume that other large cities (population in excess of 100,000) and with particulate levels in excess of 100 $\mu gm/m^3$ will eventually find it necessary to install similar

equipment. There are 50 cities in the United States fulfilling both requirements, and they include almost 28 million telephones. Extrapolating the Manhattan data to these areas yields a total annual cost to the country of slightly over $1 million. These are classed as preventive costs, even though part is for maintenance of the filters.

5.3.13 Maintenance Costs

Maintenance costs as we use them here are the costs of cleaning, repairing, replacing, and in any way restoring a piece of otherwise defective electronic equipment to enable it to perform its initial function.

When maintenance costs represent a significant fraction of the economic effect of air pollution on a category of components, we have not listed them for each category, but instead, have lumped them all together as one item. We do this because maintenance, as we have defined it, is performed mostly on equipment rather than components and costs, therefore, are not separable by component category.

Maintenance costs result from a wide variety of operations, but for simplicity, we will divide them into two major groups: cleaning and everything else. Cleaning was selected separately because electronic equipment operators are becoming increasingly aware of the damaging effects of dirt and may have adopted formal cleaning programs. One company, the M. P. Odell Company of Cleveland, Ohio, has discovered that electronic instruments frequently can be reconditioned without replacing parts simply by cleaning the entire instrument to remove conduction paths created by dust, dirt, tobacco smoke or other air-borne contaminants. The company has developed a solvent which is used with a cleaning unit and a dryer to perform the cleaning operation. The units and the solvent are sold to other companies; M. P. Odell does not do the cleaning itself.

The time required on the average to clean an instrument such as a vacuum tube voltmeter is about one-half hour. This estimate was supplied by Odell and corroborated by a user of the system, and it includes time necessary to remove the instrument from its case and to replace it after drying. The

cost for the solvent is about $0.50 per cleaning. Odell estimates that his systems are currently used for approximately one million instrument cleanings per year. If labor costs are $5 per hour, it may be seen that the present yearly cost of cleaning instruments with the Odell system is about $3 million. Of this we estimate that two-thirds, or $2 million, is attributable to air pollution.

Extending this analysis to the instruments that are not cleaned leads to an even greater cost. Sales of testing and measuring equipment in the United States has averaged about $500 million per year for the last 5 years. Assuming an average life of 5 years and an average acquisition cost of $1,000 per instrument, we estimate that there are about 2.5 million instruments of this type in use at the present time. Maintenance costs, in our experience, average about 2% of acquisition costs, or about $50 million per year for these 2.5 million instruments.

The most common maintenance procedures involve nothing more than changing tubes, a function not at all related to air pollution. The most expensive maintenance, however, probably is related to air pollution because it must include relating malfunctions to leakage paths, discovering the leakage paths and then removing them. Odell's experience has convinced him that accumulation of dirt and grime are "major" causes of instrument instability or malfunction. The fraction of maintenance costs attributable to air pollution, therefore, is certainly greater than 10% and probably less than 50%. If we conservatively estimate 20%, we arrive at an annual cost of $10 million for maintenance.* Adding this to the preceding $2 million yields an annual total cost of $12 million for the maintenance of all electronic instruments.

5.3.14 Summary of Costs

The economic impact of air pollution on electronic components as determined by the survey of over 100 manufacturers and users of these components is significant for its low magnitude. All of the data discussed in the previous sections are summarized in Table 5-1, which shows that the total annual cost is about $15.5 million.

There are two major uncertainties in this figure. First, some of the data simply are not available. In this category, the most obvious

Table 5-1. Summary of Costs, Effects of Air Pollution on Electronic Components

	Preventive Costs	Maintenance Costs	Residual Costs
	($000)	($000)	($000)
1. Semiconductors	0	0	0
2. IC	1,360	0	0
3. TV Picture Tubes	0	(Included in Line 12)	Not available
4. Capacitors	0	0	0
5. Resistors	0	0	0
6. Power & Special Purpose Tubes	0	(Included in Line 12)	Not available
7. Connectors	(Included in SRI Study)	"	0
8. Transformers	0	"	0
9. Relays	(Included in SRI Study)	0	Not available
10. Receiving Tubes	0	0	0
11. Crystals	0	0	0
12. Maintenance		12,000	
13. Users	1,000	1,200	
	2,360	13,200	

pieces of missing data are those which would tell us the cost of components that fail or otherwise become inoperative due to the damaging effects of air pollution. The three components most likely to be vulnerable to this fate would seem to be TV picture tubes, cathode ray tubes, (included with power and special purpose tubes) and relays. Other components are protected by encapsulation, potting, protective coatings and the like, to the extent that they would suffer a similar fate only in a small degree.

Second, while the procedure for selecting companies to be interviewed assured that all major manufacturers were included, still limitations of time and money meant that some related users were left out. To estimate the magnitude of these omissions, the New York City Police Department, a major user of communications equipment, was contacted. No new significant data were developed, and we conclude, therefore, that other electronics equipment users likewise would account for tangible but diminishingly small increments of cost.

The combined effect of these two factors results in an uncertainty we estimate to be no less than $\pm$20% and certainly no greater than $\pm$50%. A value of $\pm$30% seems probable.

6. RECOMMENDATIONS

One area of potentially great economic impact indicated by the present study is the cost of long-term effects of air pollution on semiconductors and integrated circuits. At present, costly steps are being undertaken to protect these components from effects of contamination during both manufacturing and use. These include the use of filtration of incoming air at manufacturing facilities, the use of clean rooms for fabrication and assembly, and the use of expensive materials for encapsulation of the components. In part, this is done to protect against contamination induced by handling and in part to protect against airborne contaminants. Little has been reported as to the potential long-term effects of the airborne contaminants on the function or reliability of the components. The protective measures are being taken on the assumption that there may be such long-term effects. This is supported by discussion with ITT Technical Staff personnel. In the event that it could be demonstrated that the long-term (10 to 20 years) effects are not significant, less costly materials could probably be employed with a consequent reduction in the cost of manufacture. To develop data to determine if the long-term effects do require protective measures, a program of accelerated life testing would be required. It is recommended that such a program be considered. In general, such a program would include controlled experiments to determine the effects of major air pollutants on the operation and life of a variety of semiconductor and integrated circuits using no protective measures except for cleaning and also using the present and planned encapsulation techniques. The output of the study would be a determination of the contribution of these measures to the reliability of the components.

Although a survey of major manufacturers (paragraph 4.1.2) exposed particulate matter as the major source of damage to electronic components, the statistical survey (subsection 4.3) illustrated a deplorable deficiency in our knowledge of the quantitative relationship between

particulate concentration and equipment failure. Capabilities exist, however, which would enable measurement to be made from which data necessary for significant statistical analyses could be made. We refer to mobile monitoring laboratories equipped to measure a wide variety of pollutants and which can be moved easily to the exact site where it is desired to make measurements. The impact of such a study would be a more quantitative understanding of the economics of particulate control.

7. ANNOTATED BIBLIOGRAPHY

Influence of Atmospheric Contaminants on Corrosion--Literature Report, Muffley, Harry C., Department of the Army Project Number 1-A-0-24401-A-109, AMC Code No. 5026.11.803, Report No. 63-2041, June 13, 1963.

Corrosion preventive coatings are currently designed to prevent moisture from coming in contact with the metal surfaces. Corrosion due to moisture alone is very slow; however, the interaction of moisture and atmospheric contaminants accelerates the rate of corrosion. The fact that these two, moisture and atmospheric contaminants, vary independently, makes it difficult to predict the corrosion behavior of a given area.

Literature in this field of endeavor was reviewed with the following questions in mind:

1. What contaminants contribute to atmospheric corrosion?
2. What is the mechanism of atmospheric corrosion?
3. What techniques are available for determining atmospheric contamination?

"Mechanisms by Which Ferrous Metals Corrode in the Atmosphere," Larrabee, C. P., Corrosion, Volume 15, October 1959, p 526t-529t.

The electrochemical theory of corrosion, by which the corrosion of steels in solutions is readily explained, also is used to explain the start of atmospheric corrosion on ferrous surfaces. Effect of contaminants both in the atmosphere and on the steel surface is described. Experiments leading to this conclusion are illustrated.

The part played by various alloying elements in retarding atmospheric corrosion, once a rust film is formed, is discussed. The relative effects of heavy and light deposits of sea salt on ferrous specimens are shown.

Corrosion Prevention/Deterioration Control in Electronic Components and Assemblies, Sparling, R. H., U. S./Army Missile Command, Redstone Arsenal, Alabama, December 1965 (143 pages).

This engineering report provides information to designers and manufacturers concerning the effect of corrosion, the subsequent degradation of electronic products and the techniques for the prevention of corrosion. It covers both metallic and non-metallic materials and includes discussions of metal couples which will result in galvanic corrosion. No separate deliberate categorization is made by the author for corrosion due to natural elements and corrosion due to atmospheric pollution, but most of the information is clearly presented so that the causes are readily separable.

The deterioration of both metals and non-metals is discussed.

"Effects of Air Pollution on the Atmospheric Corrosion Behavior of Some Metals and Alloys," Tice, E. A., Journal of the Air Pollution Control Association, Volume 12, Number 12, December 1962.

When exposed to atmospheric pollutants, metals corrode in a manner which depends upon the constituents of the pollutants. Designers, therefore, are faced with the problem of choosing a particular alloy or metal which will show the best resistivity to pollutants known to exist at the location of a proposed structure.

Data are presented showing the relative corrosion rates for various metals for areas of Europe and the United States.

It is concluded that SO_2 is the most critical air pollutant from the standpoint of corrosion and that it is aggravated by soot.

Inquiry Into the Economic Effects of Air Pollution on Electrical Contacts, Robbins, Robert C., Stanford Research Institute, April 1970 (58 pages).

Prevention of contact failure in low voltage contacts is the largest problem area in which pollution effects on electrical contacts are found. Protection is afforded by the use of air conditioning and purification equipment or by precious metal plating. Air conditioning costs attributable to air pollution are estimated to be $25 million per year, plating costs are $20 million, other costs (loss, research, high voltage flashover) are $19 million, for a total of $64 million.

The Corrosion and Oxidation of Metals, Evans, U. R. Arnold, London, 1960, Chapter XIII, "Atmospheric Corrosion."

Atmospheric corrosion can be divided into three types: dry, damp, and wet. The first category includes the development of oxide films and the tarnishing of certain metals when exposed to sulfur compounds. Damp corrosion becomes serious when humidity exceeds a critical value--about 70%. The fogging of nickel, bronze disease, production of rust-spots, and filiform attacks are examples. The effect of air pollution on outdoor corrosion is discussed.

"The Effect of Air Pollution on Electric Contacts," Antler, Morton, Gilbert, Jay, Journal of the Air Pollution Control Association, Volume 13, No. 9, September 1963, pp 405-415.

Air pollution is a major course of the degradation of electric contacts. Laboratory accelerated aging tests involving polluted environments are developed, based on field experience. Cause-effect relationships are established which aid in materials selection and the development of connector designs.

"Beware of Electronic Dirt," Manko, H. H., Electronic Design 24, November 22, 1969.

Erratic behavior and certain frequently encountered equipment malfunctions can be drastically reduced through a thorough understanding of the role of electronic dirt. Of the two types of dirt, particulate matter and foreign films, the latter is the most harmful. Final cleaning is not always feasible, however, and may be costly. Solvents are discussed and three case histories illustrate the dramatic results achieved by cleaning.

"The Deterioration of Materials in Polluted Atmospheres," Yocum, John E., Journal of the Air Pollution Control Association, Vol. 8, No. 3, November 1958, pp 203-208.

The deterioration of materials resulting from atmospheric pollution is a serious economic loss. It is related to a number of complex atmospheric and surface reactions. Further study is required of the physical factors and the chemistry of the specific agents which lead to the ultimate damage to materials.

"Design of Telephone Exchanges for Corrosive Atmospheres," Elliott, J.F.E., Tin and Its Uses, Vol. 81, 1969, pp 8-12.

Tests were conducted with copper and its alloys to determine the effects of hydrogen sulfide corrosion. The tests were prompted by the deterioration of telephone equipment in an area of New Zealand remarkable for great geothermal activity. The concentrations of hydrogen sulfide ranged from 0.004 to 0.18ppm.

Sulfides of copper and silver are porous and do not provide a barrier against further attack. Consequently, the sulfide layer gradually increases in thickness, and having low adhesion and weak mechanical strength, eventually flakes off. In this way progressive corrosion of the metal takes place and prolonged exposure causes serious loss of the metal and possible failure of the part.

Possible solutions involving air purifying equipment, application of special finishes, and use of alternate materials are discussed.

"Corrosion of Metals by Aqueous Solutions of the Atmospheric Pollutant Sulfurous Acid," McLeod, W., and Rogers, R. R., Electro-Chemical Technology, Volume 6, No. 7-8, July/August 1968, pp 231-235.

It has been found here that the corrosion rate of a metal in an acid such as H_2SO_3, HNO_3, H_2SO_4, or HCl, having a normality between N/1 and N/10,000, is related to the concentration of the acid in accordance with the equation Corrosion rate = a x (Acid Normality) where a and b are constant for each combination of acid and metal and where the termperature is 25°C. Having determined the values of a and b for a considerable number of these acid-metal combinations, it was possible 1--to compare the corrosion rates of the various metals in sulfurous acid with those of the same metals in the well-known nitric, sulfuric, and hydrochloric acids, and 2--to determine the corrosion rates of the metals in sulfurous acid of different normalities.

"Creeping Silver Sulfide," Egan, T. F. and Mendizza, A., Journal of the Electrochemical Society, Vol. 107, No. 4, April 1960.

When a gold-plated silver plate was exposed to sulfur vapor, silver sulfide formed at pores in the gold plating, but in addition, spread radially outward over the gold surface.

The same experiment using rhodium and silver revealed needles of silver sulfide at the bimetallic juncture, but no creepage of silver sulfide.

"Mechanism by which Non-Ferrous Metals Corrode in the Atmosphere," Aziz, P. M. and Godard, H. P., Corrosion, Vol. 15, October 1959, pp 529t - 533t.

Literature dealing with the mechanism by which non-ferrous metals corrode in the atmosphere is reviewed, particular emphasis being given to the important series of papers published by W. H. J. Vernon and his co-workers in the period extending from 1923 to the present. The influence of the common atmospheric constituents is discussed and related to the chemical composition and properties of the corrosion-produced film formed. The influence of these on the atmospheric corrosion rate is also discussed in relation to the nature of the corrosive atmosphere. The atmospheric corrosion of nickel, copper, zinc, aluminum and magnesium is discussed.

The Tarnishing Behavior of Silver-Palladium Contact Surfaces, and its Relationship to Accelerated Testing, Crossland, W. A., and Knight, E., Standard Telecommunications Laboratories, Harlow, Essex, England.

Silver and silver-palladium alloys were exposed to various sulfur-containing atmospheres and the following results were noted. The rate of sulfidation of silver increases with illumination. Quantitative rates of sulfidation are given for silver and silver-palladium exposed to various concentrations of H_2S and to flowers of sulfur. A given thickness of Ag_2S gives rise to a larger increase in contact resistance on AgPd than on Ag.

"Combating the Effects of Smog on Wire-Spring Relays," Hermance, H. W., Bell Laboratories Record, Volume 44, February 1966, pp 48-52.

Inspections in the Los Angeles central offices of the Bell Laboratories revealed that cracking appeared when accumulated deposits of fine airborne dusts collected on insulating surfaces around stressed nickel-brass wires in an environment of unregulated humidity. Cracks invariably started where the dust deposited on the wire. No cracking was observed on wires free of dust deposits nor was there any cracking when the humidity was kept below 50%. Further investigation correlated the cracking with moisture absorbing dusts containing high nitrate concentrations.

"The Nature of Corrosion of Zinc by Sulfurous Acid at Ordinary Temperatures," McLeod, W., Rogers, R. R., Corrosion-NACE, Volume 25, February 1969, pp 74-76.

Corrosion rate data are presented for zinc in (1) a combination of sulfur dioxide, water vapor and air, and (2) aqueous solutions of sulfurous acid in the absence of air, at ordinary temperatures. It is shown that the rate depends to a considerable extent on the form in which the sulfurous acid occurs. Information as to the nature of the corrosion products is presented.

"Sulfur Dioxide Porosity Tests for Coatings of Gold and the Platinum Metals on Substrates of Copper and its Alloys, Nickel, Silver," Clarke, M., and Leeds, J. M., Transactions of the Institute of Metal Finishing, Volume 46, 1968.

This report describes tests devised to detect porosities in platings of gold, platinum, alloys of both, nickel and silver. The test, which involves a 24-hour exposure to sulfur dioxide, is intended to replace currently used electrographic tests and 48-hour sulfur dioxide-hydrogen sulfide tests. Results show that such a test could complement the latter two tests and, in certain cases,replace either.

The significance of these tests is the implication that SO_2 permeates noble metal coatings and attacks the substrate.

"Evaporated Metal Films as Indicators of Atmospheric Pollution" (Part I), Lodge, J. P. and Havlik, B. R., International Journal of Air and Water Pollution, Vol. 3, No. 4, pp 249-252.

Glass slides covered with films of aluminum, iron, lead, copper, and silver were prepared and exposed to the atmosphere in the Cincinnati area. Corrosion products were identified by X-ray and microchemical means.

Results showed that aluminum was the most dependable indicator of general atmospheric corrosiveness, although silver appeared specifically sensitive to a small group of pollutants such as halogens, ozone, and sulfur compounds. Lead corroded so rapidly that it was difficult to interpret. Iron was primarily responsive to humidity.

"Evaporated Metal Films as Indicators of Atmospheric Pollution" (Part II), Lodge, P., and Frank, E. R., International Journal of Air and Water Pollution, Vol. 6, pp 215-221.

An attempt was made to utilize the electrical resistance of the metallic films as an index of the rate of attack of the corroding agents. A simple, inexpensive technique was evolved for the continuous recording of the rate of corrosion by pollutants in the atmosphere. The recording system and the resulting graphs are presented and analyzed. It was concluded that there is a direct relationship between gross atmospheric features associated with the accumulation of substances in the air that are corrosive to metals and the rate of resistance change in metallic films.

Systems Analysis of the Effects of Air Pollution on Materials, Salmon, R. L., MRI Report, Contract CPA-22-69-113, MRI Project No. 3323-D, 15 June 1969-14 January 1970.

While it has been known for some time that materials are damaged by the action of air pollutants, information on the exact mechanisms and rates of attack is available only for a small number of specific material-pollutant combinations, notably zinc-SO_2, cotton-SO_2, and rubber-O_3.

In spite of the paucity of information, it is possible to estimate the economic losses caused by air pollution. In order to maintain all materials as clean as they would be in the absence of air pollution would require the expenditure of an estimated $100 billion per year. The direct economic losses caused by deterioration are estimated to be as high as $9.5 billion per year.

Soiling of paint, zinc, and flat glass (all used primarily as outdoor-exposed surfaces of buildings) is the cause of the major portion of economic loss.

In order to make further progress in the assessment of air pollution damage to materials, research is needed to obtain precise data on both physical-chemical and economic aspects of significant material-pollutant interactions. There is also a need for evaluation of the procedures used to obtain such data.

"The Role of Copper (II) in the Oxidation of Ferrous Hydroxide Colloid with Special Reference to the Corrosion of Iron in an SO_2-Containing Environment," Inouye, Katsuya, Journal of Colloid and Interface Science, Volume 27, No. 2, June 1968, pp 171-179 (Extract).

The presence of sulfur dioxide influences the rate of corrosion of iron through a change of SO_2 to SO_4--ions, further accelerating the oxidation

reaction. Evidence of the existence of $FeSO_4$ in the corrosion product, usually in the boundary between the metal surface and the oxide layer, is reported. In the presence of copper, however, the oxidation is inhibited.

"Dirt and Calibration," Odell, M. P., Measurements and Data, January/February, 1969.

Malfunctions of electronic equipment are frequently caused by contamination such as dirt and oily deposits that create electrical leakage paths around input terminals and components. These deposits can be successfully removed by the use of proper solvents and if repair time and costs are to be kept low, cleansing ought to precede the replacement of parts. Examples are given.

"Freeways vs. Contamination Control in California," Contamination Control, April 1970.

This article is of interest mainly because it involves the first legal case in history wherein a suit was filed against a state to obtain a settlement to offset the cost of combating contamination due to the intended construction and operation of a freeway passing near the plant. The company involved is ITT Jennings and the settlement request involved a figure of approximately $1,000,000. The article includes a chart which shows environmental conditions before the construction of the freeway, during the construction of the freeway, after the completion of the freeway, and the normal future which takes into account a normal community growth over a five-year period, from 1971 to 1976. The case against the California State Highway Department was denied a hearing in February 1969, but the case has been appealed to California higher courts.

"The Electronics Industry," Dunlap, Lloyd W., Chemical and Engineering News, November 30, 1970.

A number of chemical problems in the manufacture of electronic components, several of which either originate directly, or are indirectly caused by pollution of the atmosphere are cited.

Semiconductor manufacture requires process water with resistivities of 15 megohms. To obtain water with such high resistivity, distilled water, which normally has resistivities of about 1 ohm, must be deionized a number of times.

Similarly, the manufacture of MOS integrated circuit cards requires procedures that avoid any contamination of the surface layer of silicon dioxide by sodium, potassium, lithium, calcium, aluminum, magnesium, barium, and strontium ions. Such purity control inevitably involves extraordinary measures (which are described) to prevent atmospheric pollution of the materials through all stages of manufacture.

"Environment Simulation for Studying the Effects of Air Pollutants on Computers," Steading, T. Walter, APCA Journal, Vol. 15, No. 3, March 1965.

This paper describes a study directed towards the laboratory simulation of parameters of the office environment related to airborne gaseous and particulate pollutants and initial operating experience of a particulate test chamber, instrumentation, and control techniques. Also, discussed is the design of a simple gaseous test chamber being constructed. Gas dilution procedures, control and general operating approach are described.

"Measurement and Simulation of the Computer Environment," Steading, T.W., and Paulsen, J. N., Proc. of the Institute of Environmental Science, Annual Meeting, 1967.

This paper describes three field investigations made by IBM which resulted in better definitions of earth environmental parameters of man-operated commercial and industrial computers. The environments of interest were floor vibration, airborne dust, and conducted electrical switching transient noise. The techniques used in defining these environments as well as experimental methods used in simulating them are described.

General summaries derived from the collected data are presented.

"The Effects of Air Pollution of Electrical Contact Materials: A Field Study," Chiarenzelli, Robert V., and Joba, Edwin L., Journal of the Air Pollution Control Association, Vol. 16, No. 3, March 1966.

A long-term field and laboratory program designed to determine and understand the effects of air pollutants on the performance of electric contact materials has reached the one-year mark. An extensive variety of metals has been exposed at six field environments, for periods up to one year (August 1963 to August 1964). These environments were selected to provide

a wide range of air pollutants in typical data processing or process control situations. The program undertakes to determine material degradation as a function of time and environment. The important air pollutants at the field sites are measured regularly, and materials are returned periodically to the laboratory for evaluation using techniques developed specifically for this program. The results of the program to date are presented, and preliminary correlations are drawn.

"The Relation of Thin Films to Corrosion," Rhodin, R. H., Corrosion, Vol. 12, No. 9, 465t-475t (1956) September.

Recent studies of thin oxide films isolated from stainless steels and other ferrous alloys have provided new information on surface properties. Correlations between the unique compositional and structural properties of thin films and alloy corrosion behavior in various corrosive environments have been established.

Evaluation of the resistance to pitting corrosion of silicon-modified Type 316L stainless steel is described as a typical example of an application of a film study to corrosion research. In this case, improved corrosion behavior was correlated with a mutual film-enrichment of silicon and molybdenum and a film-depletion of iron. Experimental alloys of improved purity were prepared and evaluated. Effects of alloy purity, carbon content, and alloying additions were found to influence strongly surface behavior and corrosion resistance.

The mechanism of resistance to pitting corrosion and the protective nature of the associated oxide films are interpreted in terms of the chemistry of hydrated heteropoly acids containing oxides of silicon and molybdenum.

The following group of nine papers, all delivered at the IEEE Winter Power Meeting in New York, January 31 - February 5, 1971, are on the general topic of high voltage insulator flashover, a subject discussed in the SRI Report (Ref. 13), but published too late to be included in that report. They are included in this bibliography to augment the SRI Report and because they are part of the literature on air pollution damage effects.

"A Survey of Insulation Contamination in the United States and Canada," Part I, Transactions of the IEEE, Paper No. 71 TP 133-PWR, February 19, 1971.

Because of the growing problem caused by insulator contamination due to both industrial pollution and natural deposits, a Working Group of the Lightning and Insulator Subcommittee was formed to study the problem. The first objective was to determine the extent of the problem in the U. S. and

Canada, and to determine the various kinds of contaminants and the most severe weather conditions that cause transmission line outages. A survey was conducted by sending questionnaires to 90 utilities. A total of 309 case histories were reported. This report summarizes the answers to questions regarding contaminants and insulator types. It also sheds some light on the preventive measures most frequently undertaken by the utilities and the degree of success of each action.

"Switching Surge Performance of Contaminated Insulators," Turner, F.J., Macchiaroli, Transactions IEEE, Paper No. 71 TP 141-PWR, December 1, 1970.

The "wet contaminant" test method, originally developed for use with alternating voltage, is extended for use with switching surges. In order to evaluate insulators under conditions where dry bands would form, it was found necessary to first energize the contaminated insulators with alternating voltage before applying the surges. Included in the investigation are the effect of front time and tail time on the critical flashover voltages, and a comparison of the switching surge performance of five insulator types under various levels of contamination.

"A Study of the Performance of Contaminated Insulators Under Various Test Conditions," Kawai, M., Transactions IEEE, Paper No. 71 TP 132-PWR, December 15, 1970.

Two contamination test methods have been examined for the difference in assumptions used as the basis of each method. Dynamic surface impedance of insulators in a slow-wetting condition is remarkably influenced by the voltage across the insulator unit, which causes nonlinearity of insulation strength with insulator length. On the other hand, the surface condition can be represented as resistance in wet contaminant tests. This difference in surface condition naturally leads to disagreement in the results. It has been concluded to be of limited utility to discuss the order of merit for several insulators with different test methods, since any contamination method cannot simulate all aspects of this problem.

"Lightning Impulse Flashover Characteristics of Long Disc Insulator Strings Under Polluted Conditions," Okada, T., Koga, S., and Kimoto, I., Conference Paper IEEE, Paper No. 71 CP 144-PWR, December 1, 1970.

Lightning impulse flashover voltage of long disc insulator strings showed great reduction under polluted conditions: maximum 25% reduction for 25-unit string and maximum 35% reduction for 45-unit string. Because

of this reduction, lightning impulse flashover characteristics of disc insulators are to have great significance for insulation design of UHV lines. This reduction in flashover voltage of insulator strings varied the flashover paths of insulator assemblies equipped with arcing horns; the lightning impulse flashovers tended to take the paths creeping along the insulators under polluted conditions, in spite of the fact that the flashovers take the paths between the arcing horns and stay away from the insulators under clean conditions. With deep-rib type disc insulator strings, the reduction due to pollution was almost nil for positive polarity.

"The Effects of Pollution and Surface Discharges on the Impulse Strength of Line Insulation," Lushnicoff, N. L. and Parnell, T. M., Transactions IEEE, Paper No. 71 TP 143-PWR, December 1, 1970.

The effect of surface discharges on the ability of polluted insulators to withstand lightning and switching surges has long been a matter of conjecture. This paper describes combined power frequency and impulse voltage tests on 66 kV and 132 kV insulator strings. The tests have shown that an appreciable lowering of both lightning and switching surge strength may occur in the presence of pollution layers. The worst lowering of impulse strength (about 50%) has been found in cases where drying of the pollution has reduced the leakage current almost to zero by the production of extensive dry bands on the insulator surface.

"Effects of Dew and Fog on Insulator Breakdown Strength," Berger, K. and Chowdhuri, P., Conference Paper IEEE, Paper No. 71 CP 140-PWR, December 7, 1970.

This paper describes the sparkover characteristics of insulators subjected during 20-80 minutes to a 50-Hz voltage under simulated conditions of dew and fog in the laboratory. Results obtained with different materials are discussed. A test procedure is proposed for the purpose of reducing the duration of tests. It consists of the superposition of a surge voltage of slow rising front on the rated 50-Hz voltage applied to the insulator.

"A Possible Solution to the Insulator Contamination Problem," Moran, J. H., and Powell, D. G., Conference Paper IEEE, Paper No. 71 CO 41-PWR, January 31 - February 5, 1971.

A new semi-conducting glaze is introduced as an excellent solution to the growing problems posed by contamination of electrical insulation. The method of use is given, as are the results of both laboratory and field tests on station posts and suspension insulators. Discussions of the electrical characteristics and operation of the glaze and the economics of its use are included.

"Analysis of Dielectric Recovery with Reference to Dry-Zone Arcs in Polluted Insulators," Rizk, F.A.M., Conference Paper IEEE, Paper No. 71 CP 134-PWR, January 31 - February 5, 1971.

In A.C. systems the conditions of reignition and recovery of dry zone arcs on polluted insulators subsequent to current zero of the leakage current, are of fundamental importance in determining the possibility of a flashover. In this paper dielectric recovery of free-burning arcs in air in the range 50-700 mA is analyzed on the basis of an approximate solution of the energy balance equation. The results are presented in the form of a general relation between the critical voltage necessary to maintain an arc in units of the flashover voltage of the discharge gap at ambient temperature, and the amplitude of the leakage current. In view of the complicated nature of the problem the agreement between theory and previous field and laboratory experiences is satisfactory.

"A Criterion for A. C. Flashover of Polluted Insulators," Rizk, F.A.M., Conference Paper IEEE, Paper No. 71 CP 135-PWR, December 29, 1970.

On the basis of the analysis of dielectric recovery of dry-zone arcs presented in a companion paper, the critical a.c. voltage per unit length of creepage path necessary to maintain the arc on a polluted insulator surface is calculated. Calculations cover the range of pollution resistance per unit creepage length of 1 - 6 kohm/cm. From this a new criterion for a.c. pollution flashover of insulators with uniform pollution resistance along the leakage path is deduced. It is shown that the present theory agrees better with the experimental findings than does the previous d.c. theory. Moreover the present theory agrees satisfactorily with the predictions of dimensional analysis.

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51. "A Criterion for A. C. Flashover of Polluted Insulators," Rizk, F.A.M., Conference Paper IEEE, Paper No. 71 CP 135-PWR, December 29, 1970.

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9. EXHIBITS

EXHIBIT 9.1
Interviews with Manufacturers of Electronic Components

Company and Location	Person Interviewed	Product
Admiral Corporation Chicago, Illinois	Vincent Kamler Director-Engr.	Color TV Tubes
Aerovox Corporation Olean, N. Y.	Manager, Mech. Engineering	Ceramic Capacitors .050" sq. x .088 long to 1.5" square
Allen Bradley Milwaukee, Wisconsin	Harold Zoble R. Polakowski Al Smith Design Engineers	Resistors and Potentiometers
Amperex Electronic Corp. Slatersville, R. I.	Gullio Masullo Chemist	X-ray image intensifiers Plumicon tubes
Amperex Electronics, Inc. Hickesville, N. Y.	Michael J. Pawelko Engrg. & Applications	Tx Tubes 5 W to 15 KW Microwave tubes for radar and cooking ranges X-ray tubes Radiation counters
Amphenol Connector Div. Broadview, Ill.	Ned Spangler Vice President, Manufacturing	Connectors
Amphenol RF Division Danbury, Connecticut	Eugene Makl Vice President, Manufacturing	RF Connectors 3/8" dia. x 1/2" long to 3" dia. x 6"long Coaxial switches Microwave components
Bliley Electric Corp. Erie, Pennsylvania	George Wright Mgr. Marketing	Crystals
Centralab Div. of Globe-Union, Inc. Milwaukee, Wisconsin	Gerald Stoughton Mgr.-Corporate Facilities	Ceramic capacitors Package circuits Hybrid circuits Potentiometers Switches Semiconductors, electroluminescent devices - Calif.

Company and Location	Person Interviewed	Product
Cinch Manufacturing Elk Grove, Ill.	R. Scott Modjeska Concerned with air and water pollution control	Connectors Tube sockets Terminal blocks
Cornell Dubilier Electronics New Bedford, Mass.	Robert Stone Mgr. -Marketing	Oil-filled, hermetically sealed capacitors-1/2 in.^{3} to 2000 in.^{3}
Cornell Dubilier Electronics Fuquay-Verina, N. C.	Robert M. Butler Mgr. -Marketing	Relays-Enclosed and open Antenna Rotors Vibrators-DC & AC Power Supplies
Cornell Dubilier Electronics	John Hand Mgr. -Engineering (Electrolytic Capacitors) William Colman Mgr. -Engineering (Paper/film capacitors)	Electrolytic Capacitors (Al & Ta foils) Paper and Film Capacitors (non-metallic cases) 1/8 x 5/16 to 1" x 3"
C. P. Clare & Co. Chicago, Illinois	W. O. Thompson Vice President Mfgr.	Relays milliwatts to 100 amps. P. C. boards Lighted pushbuttons Keyboards Stepping switches Timers
CTS Knight, Inc. Sandwich, Illinois	R. T. Bensen Quality Control Engr.	Crystals Crystal controlled oscillators Filters Components
Dale Electronics, Inc. Columbus, Nebraska	Elsie Ita Secretary to Regional Manager	Bare wire wound resistors Carbon film resistors Metal film resistors Bobbin wire wound - coated wire

Company and Location	Person Interviewed	Product
Electronics Center (Thordarson & Meissner) Mt. Carmel, Illinois	Wayne Morris Admin. Asst.	Transformers (Ultra miniature to 7 KVA)
Erie Technical Products, Inc. Erie, Pennsylvania	W. T. Crotty Vice President, Sales	Fixed & variable ceramic capacitors Chip size up to 2" Mica Capacitors Carbon Resistors Semiconductors
Fairchild Semiconductors Mt. View Calif.	Dr. J. Early Director R & D	Semiconductors and I. C. 's
Fairchild Semiconductor Products Mountain View, Calif.	Dr. O. J. Trapt. Mgr., Quality Assurance	Integrated Circuits
General Electric Semi-conductors Auburn, N. Y.	Finis Gentry Mgr.-Engineering Ed Izzo Mgr.-Mfg. Engineering	Semiconductors
General Electric Hudson Falls, N. Y.	Donald J. Meyers Mgr.-Manufacturing	Capacitors (includes plastic and metal foils)
General Electric Co. Tube Products Dept. Owensboro, Ky.	James F. Madole Mgr.-Engrg.	Receiving Tubes Microwave Tubes Thyratrons Industrial CRT's LRT building
Guardian Electric Mfg. Co. Chicago, Illinois	Donald Schuette Works Manager	Relays Solenoids Switches
International Crystal Mfg. Co., Inc.	Paul Freiland Vice President, Production	Crystals Crystal Oscillators
ITT Cannon Santa Ana, Calif.	Ralph Alexander Staff Chemist	Connectors

Company and Location	Person Interviewed	Product
ITT Headquarters New York, N. Y.	Ray Berry Asst. Tech. Director for Switching Components	Electrical Components
* ITT Jennings San Jose, Calif.	M. C. Budde Mgr. -Mfg.	Vacuum capacitors and switches
J. W. Miller Co. Campton, Calif.	F. T. Scott	RF Coils and transformers
Macklett Labs. Stamford, Conn.	Dr. Doolittle Engr. Mgr. - R&D	Microwave and Power Tubes
Macklett Labs. (Div. of Raytheon) Stamford, Conn.	Carmen Ramic Mgr. -Marketing	Image tubes Power tubes
Mallory Capacitor Corp. Indianapolis, Ind.	Harry Nieders Mgr. -Marketing	Ta Electrolytic Capacitors Al Electrolytic Capacitors AC Oil Capacitors
Motorola Semiconductor Products, Inc. Phoenix, Arizona	Joe Flood Mgr. -Quality Assurance	Semiconductors and Integrated circuits
National Electronics Geneva, Ill.	Robert Streaker Vice President, Div. Manager SEMCO Div.	Semiconductors
* National Semiconductor Santa Clara, Calif.	Ed Thompson Manager, Quality Assurance	Integrated circuits
National Semiconductor Towson Office, Md.	Tom Reynolds Dist. Sales Mgr.	Semiconductors and Integrated Circuits
Ohmite Corp. Skokie, Illinois	L. Berkelhamer Vice President, Engineering	Resistors Switches Variable transformers Relays

*Field visit in addition to telephone interview

Company and Location	Person Interviewed	Product
Philadelphia Division of TRW (IRC) Philadelphia, Pa.	Fred Rocchi Operations Manager	Carbon Resistors 1/4W to 1W
Photocircuits, Inc. Glen Cove, N. Y.	George Messner Director - Research	Printed circuit boards DC motor with printed armature
Potter & Brumfield Princeton, Indiana	Wayne Harper Sales Supervisor	Relays
Raytheon - Industrial and Cathode Ray Tube Division	Warren Davis Chief Engineer	Cathode Ray Tubes
Raytheon - Microwave Tube Division	Ed Downing Manager Quality Assurance	Microwave Tubes
RCA - Electrio-Optical and Power Tube Div. Lancaster, Pa.	Tom Lewis Application Engineer Photo-multiplier Tubes	Photomultiplier Tubes
RCA Electrio-Optical and Power Tube Div. Lancaster, Pa.	Dr. Morris Slater Engineering Specialist	Electric Optical Div. Power tubes
RCA (Image Tube Division) Lancaster, Pa.	Frank Keith Mgr. -Marketing	Image tubes Photomultiplier tubes
RCA Microwave Tube Div. Harrison, N. J.	John Kucera Mgr. -Quality Assurance	Microwave tubes
RCA Microwave Tube Division Harrison, N. J.	Joe Smack Environ. Engineer	Microwave tubes
Sangamo Electric Co. Capacitor Division	Emil Blase Director-Engineering	Mica capacitors Electrolytic capacitors Paper, Oil capacitors Power factor capacitors size range-picofarad to farad

Company and Location	Person Interviewed	Product
Sigma Instrument Inc. Braintree, Mass.	D. A. Belcher Sales Service Mgr.	Relays Reed General Purpose Sensitive Digital stepping motors Outdoor lighting controls
* Signetics, Inc. Sunnyvale, Calif.	K. G. Lemmons Manager, Qual. Assurance	Active Integrated Circuits
Sprague Electric Co. North Adams, Mass.	Dr. Dan Norton Engrg. Specialist	Ceramic Capacitors Passive integrated circuits
Sprague Electric Co. North Adams, Mass.	William Allison Technical Advisor	Film capacitors Paper & oil capacitors Electrolytic capacitors
Stancor Corp. Chicago, Ill.	R. J. Reigel	Transformers Audio to 3 KVA
Sylvania Seneca Falls, N. Y.	Robert Peters Manager-Marketing	CRT's Color TV Tubes
Texas Instruments Dallas, Texas	Dr. Gordon Peattie Mgr. -Quality Assurance Dept.	Semiconductors and active integrated circuits
Triad/Utrad Venice, Calif.	Bob Larson Market Manager Hank Jajaroski Quality Control Mgr.	Transformers
TRW-IRC Phi[illegible]delphia, Pa.	Dale Fisher Mgr. - Marketing	Carbon Resistors 1/4 to 1 W Wire Resistors 1 to 2 W
Tungsol Livingston, N. J.	J. J. McGarth Plant Engineer	Hydrogen Thyratrons Silicon Diodes Electronic Power Packs
United Transformer Corp. New York, N. Y.	Burt Yudin Engrg. Manager	Transformers 1/10 oz to 520 lbs. mv to 10 kv, open with varnish dip, hermetically sealed canned with bakelite terminals

*Field visit in addition to telepnone interview

Company and Location	Person Interviewed	Product
Varian Associates Palo Alto, Calif.	H. Gardner Staff Engineer	Microwave Tubes Power Tubes Instruments
Varian Associates Eimac Division San Carlos, Calif.	R. Albertson Chief-Mfg. Engineer	Microwave tubes Power tubes
Varian Associates Eimac Division San Carlos, Calif.	Bill McAulay Manager-Appls. Engrg.	Microwave tubes Power tubes
Vector Electronic Co. Sylmar, California	C. D. Grey Mgr.-Administration	Printed circuit boards & hardware
Western Electric Co. Allentown, Pa.	Phillip Morrison ----	Integrated Circuits for Telephone System
Western Electric Co. Allentown, Pa.	Jack Coughlin ----	Integrated Circuits for use in Telephone System

EXHIBIT 9.2

Interviews with Equipment Manufacturers Using Electronic Components

Company and Location	Person Interviewed	Product
Beckman Fullerton, California	William Newton Director-Mfrg.	Analytical instruments Precision components Potentiometers Microcircuits
IBM Federal System Division Raleigh, N. C.	Dr. Don Preiss ----	Computers
McGraw Edison Company Milwaukee, Wisconsin	H. A. Van Dusen, Jr. Senior Engineer	Street Lighting Equipment
* Royco Instruments Menlo Park, Calif.	Dr. A. Lieberman ----	Particle Detecting Instruments
Varian Associates Union, New Jersey	Bill Sylvernal Mechanical Engineer	Power tubes & instruments
* Western Gear Co. Pasadena, Calif.	C. W. Yost Program Manager	Precision DC Motors

* Field visit in addition to telephone interview

EXHIBIT 9.3

Interviews with Users of Electronic Equipment

Company and Location	Person Interviewed	Product
ASTM (American Society for Testing Materials) Philadelphia, Pa.	Jim Dwyer	---
AT&T New York, N. Y.	E. P. Hodges Bldg. Engineer - NYC	Maintenance of Telephone Co. Building-NYC
AT&T Long Lines Division Washington, D. C.	Bob Scatchard Dist. Bldg. Engineer	Telephone Relay Station
AT&T New York, N. Y.	Dan Lyon Mgr. Bldg. Engrg.	Maintenance of AT&T Buildings
Bell Telephone Laboratories Holmdel, New Jersey	C. A. Russell Supervisor: Electrical Contact Contamination Studies	Materials Research in Electrical Contact Contamination
* Bell Telephone Laboratories Holmdel, New Jersey	T. F. Egan ----	Materials Research on Electrical Contacts
IBM Burlington Components Division Essex, Vermont	H. Frankel ----	Computers and component parts
IBM Engr. Eval. Lab. San Jose, Calif.	T. W. Steading ----	Computers
* M. P. Odell Co. West Lake, Ohio	M. P. Odell President	Equipment cleaning systems
Potomac Electric Power Co. Washington, D. C.	P. Benziger Asst. Vice President Generation	Power generation
Potomac Electric Power Co. Washington, D. C.	Stewart Bouchet Transmission Engineer	
Sandia Laboratories Albequerque, New Mexico	Leo Klameris ----	Materials and contamination research
Sandia Laboratories Albequerque, New Mexico	J. D. Sivinski Willis Whitfield Contamination Control Specialists	----

*Field visit in addition to telepnone interview

Company and Location	Person Interviewed	Product
Western Electric Co. Cockeysville, Md.	Len Cochran Envir. Engineer	Telephone Equipment Maintenance
Western Union Washington, D. C.	Art Carroll Area Maintenance Supervisor	Maintenance of Telephone and Telegraph Equipment
** Merck and Co., Inc. Rahway, N. J.	R. R. Johnson Project Manager	Pharmaceutical Chemicals

** Visited but not formally interviewed by telephone

EXHIBIT 9.4

Interviews with Government Agencies, Professional Associations, University Groups and Others

Organization and Location	Person Interviewed	Product
AACC - American Association for Contamination Control	W. T. Maloney ----	----
Bureau of Ships Equipment Maintenance Group Washington, D. C.	Ralph Thresher ----	Shipboard Electronic System
District of Columbia Highway Department Traffic Signal Branch	A. J. Breckinridge Branch Manager	Maintenance of Traffic Signals
Drexel Institute Philadelphia, Pa.	Dr. Henry Wohlers Prof. of Environmental Engrg. & Science	----
Environmental Engineering, Inc. Gainesville, Florida	Dr. A. Hendrickson ----	Consulting services
FAA Falls Church, Va.	John McGivern Area Facilities Chief	Maintenance of Navigation Aid Equipment for Washington area FAA
FAA, System Maintenance Services	Walt Quitter Director, System Maintenance Services	Maintenance of FAA Equipment
* Federal Aeronautics Administration Washington, D. C.	Mr. Williams Runway lighting Maintenance Engineer	Maintenance of airport runway lighting
* Federal Aeronautics Administration Washington, D. C.	Frank Opeka Branch Manager Maintenance Engineer	Engineering of FAA Maintenance of Equipment
* NASA-Goddard Research Center Greenbelt, Maryland	Calvin Hirt Reliability Engineer	Tracking Station for manned space flights
* NASA-Goddard Research Center Greenbelt, Maryland	Tom Sciacca Matls. Res. Engineer	Materials research for space craft

*Field visit in addition to telephone interview

Organization and Location	Person Interviewed	Product
NASA-Goddard Research Center Greenbelt, Maryland	Dr. Frankel Post Director- Materials Research	Materials research for manned space craft
National Bureau of Standards Gaithersburg, Maryland	Dr. Charles Marsden ----	----
Naval Test Engineering Center Hyattsville, Maryland	Mr. Smollen Test Engineer	Navy Communications System
Pima County, Arizona Health Dept. Tucson, Arizona	Dr. Roy McColdin Dir. -Environ. Health	----
San Francisco Bay Area, APCD	Dr. Milton Feldstein Director	----
U.S. Air Force Radar Equip. Maintenance Group Sacramento, Calif.	Donald Hinshaw ----	Maintenance of AF Radar Equipment
*U.S. Weather Bureau - ESSA Silver Spring, Md.	Russell Hovey Engrg. Supervisor	Maintenance of Weather Bureau Equipment
U.S. Weather Bureau Kansas City, Mo.	Harold Anderson Regional Engrg. Chief	Maintenance of Weather Bureau Equipment

* Field visit in addition to telephone interview

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PUBLISHED BY THE ELECTRO-PHYSICS LABORATORIES

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Contain results or data of a preliminary nature and do not necessarily reflect the final opinion of the Electro-Physics Laboratories; specifically intended for internal guidance and documentation only. **(Red Cover)**

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